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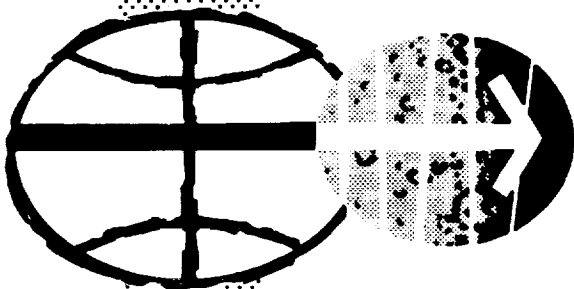
An Investigation of Volcanic Depressions

Part III

Maars, Tuff-rings, Tuff-cones, and Diatremes

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A progress report of work carried out under
NASA Research Grant NGR-38-003-012



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An Investigation of Volcanic Depressions

Part III

Maars, Tuff-rings, Tuff-cones, and Diatremes

by

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INTRODUCTION AND ACKNOWLEDGEMENTS

The literature dealing with maars, tuff-rings, tuff-cones, and diatremes is voluminous and widely scattered. Most authors have unfortunately confined their attention to either surface- or sub-surface features; few have attempted to discuss their mutual relations, the principal object of the present report. Examples have been selected from various parts of the world, and while our review is based to a large extent on available literature, it is also based largely on our own field observations in many volcanic fields, sometimes made alone and sometimes with the expert guidance of others familiar with particular areas. We have also gathered considerable information during field-studies at the Hole-in-the-Ground maar in central Oregon, details of which are presented in a separate report (Part IV). On the basis of the foregoing, we present a classification of maars, tuff-rings, tuff-cones and diatremes, and summarize their lithologic and structural characteristics at the surface and at depth, and their probable manner of formation, laying particular emphasis on the roles of fluidization and of groundwater.

For stimulating discussions and welcome guidance in the field, we gratefully record our indebtedness to the following geologists: Howel Francis of Leeds, England, for his guidance on our visit to the diatremes of eastern Scotland; B. Carter Hearn, Jr. of the U. S. Geological Survey, for an instructive visit to some of the kimberlitic diatremes of the 'Missouri River Breaks' of Montana; and Grant Heiken of Houston, for showing us some basaltic tuff-rings in central Oregon.

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1. The first step is to identify the problem.

2. The second step is to define the problem.

3. The third step is to analyze the problem.

4. The fourth step is to develop a solution.

5. The fifth step is to implement the solution.

6. The sixth step is to evaluate the solution.

7. The seventh step is to monitor the solution.

8. The eighth step is to report the results.

9. The ninth step is to conclude the project.

10. The tenth step is to close the project.

Part I. General Discussion

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Maars

The term maar, as Noll (1967) has stated in his review of terminology, has been used to describe small, nearly circular crater lakes in the Eifel, Germany, having been adopted from the Latin word 'mare' (sea). Since 1819 (Steininger, 1819, 1820, 1821), the term has also been used for volcanic craters the floors of which transect the pre-eruption surface. Many writers, unfortunately, still continue to restrict the term to low-rimmed craters that contain lakes; manifestly, however, the presence or absence of a lake depends mainly on the degree of permeability of the crater-floor and the relative position of the water-table, and hence has no genetic significance.

In the present report, the following modified version of Noll's (1967) definition is adopted.

'Maars are volcanic craters cut into the "general ground" (pre-eruption surface) and having a shape intermediate between that of a funnel and a shallow dish. They are surrounded by a blanket of pyroclastic debris of very variable thickness, in some cases reaching the height of a tuff-ring. The craters originated mainly by abrasion and slumping or by collapse along ring-faults. Late-stage eruptions may form a central tephra cone or even a lava lake.'

Accordingly, a maar may be funnel-shaped or it may be shallow and have a flat floor, and it may be surrounded by either a thin or thick blanket of ejecta. It may form by continuous enlargement during successive eruptions, intermittently, or at a late stage by subsidence along a ring-fault owing to withdrawal of magmatic support at depth. Moreover,

subsidence may be restricted to the feeding conduit and a thin collar of wall-rocks, or it may affect an area many times larger than the initial vent or vents. If subsidence plays a major role in the development of the maar, the resulting structure is in fact a small caldera. Maars in which collapse played an important, if not a dominant role are abundant, contrary to Ollier's (1967) view; examples may be seen among the Pinacate maars close to the Mexico-U. S. border and among the Eifel maars, and other examples may be deduced from collapse-structures revealed in deeply eroded diatremes that once terminated at the surface in maars.

Two main categories of maars may be distinguished, namely:

- a) those formed by the eruption of large volumes of country rocks; and
- b) those formed by subsidence brought about either by eruptions or by withdrawal of magmatic support. Needless to say, many maars are formed by a combination of these processes. Type 'a' corresponds to Noll's type A_2 , and type 'b' to his type B_1 .

In maars of type 'a', the volume of the pyroclastic ejecta equals or is larger than that of the rocks which originally occupied the site of the crater, depending, of course, on the proportion of juvenile, magmatic materials among the ejecta. In maars of type 'b', the volume of the ejecta may be smaller or larger than that of the rocks which have disappeared. For example, in the Eifel maars of type 'b', the volume of ejecta is much smaller than that of the rocks which once occupied the site of the craters; on the other hand, if abundant juvenile material was admixed with the lithic debris in the ejecta, the total volume erupted may exceed that of the crater.

The so-called Kesselthaler of the Eifel and Ollier's craters of

the Barbato type are remarkable for the lack of detectable ejecta. Apparently little but gas was discharged, and subsequently withdrawal of magma led to subsidence at the surface. These therefore belong to type 'b'. There are, however, many circular basins that subsided slowly for long periods while lacustrine and fluviatile sediments accumulated to great thicknesses on their floors, as in the Hopi Buttes, Arizona. Nothing indicates that these basins were formerly eruptive vents, but because they lie in a region rich in diatremes it may be assumed that they were formed by the withdrawal of magma that failed to break through to the surface, because it migrated underground to feed adjacent vents. Whether or not such circular depressions should be called maars is a debatable question.

Maars of types 'a' and 'b' may be surrounded by thick or thin blankets of ejecta. The amount that makes up the rim obviously depends on many factors in addition to the volume of the ejecta, e.g. the directions and velocities of winds at various elevations, the attitude of the conduit, whether vertical or inclined, the muzzle velocities of the fragments, and the morphology of the surrounding area. Hence, the thickness of the ejecta-blanket is unimportant from the standpoint of classification; it should suffice to speak of maars with low, high, or intermediate-sized rims. A maar that contains a tephra cone may be qualified as a 'nested maar'.

The shape of the crater also depends on many factors independent of those that created the initial depression, e.g. the deposition of lacustrine and peat beds on the floor, slumping of the walls, and the

growth of debris fans. Holmes (1965) thought that a distinction should be drawn between 'explosion vents' and 'fluidization craters'. The latter, in his opinion, are characterized by wide, shallow, nearly flat-floored craters with low rims, the flat floors having originated from 'expanded or boiling beds'. In our opinion, this mechanism seems improbable since it would require an even gas-flow over a large area for a long time. A multi-size particle system would not produce a surface comparable to that formed by fluidization of particles of equal size which results in 'boiling bed' surfaces. Fallback of the debris from a large, dense cloud--which is a kind of defluidization--might form a flat floor, but so can major subsidence followed by erosion and deposition of sediments within the resultant depression.

The diameter-to-depth ratios of maars show a remarkable variation. Based on figures presented by Noll (1967), the ratio is at least 3:1 and may reach 40:1. Because of enlargement of the crater by erosion and consequent decrease in depth, the ratio increases with time.

If volcanism continues after a maar has been formed, a tephra cone may be built on the floor or pyroclastic debris may accumulate to such an extent that it almost fills the crater, and so the maar becomes a tuff-ring. If renewed activity is effusive rather than explosive, a lava lake may come to occupy the crater floor or a domical pile of lava may completely bury both the floor and the rim, so that the former presence of the maar is only revealed by later erosion.

Tuff-Rings and Tuff-Cones

Not only the conduit but the crater of a maar indents the pre-eruption surface, but only the conduits of tuff-rings and tuff-cones do so, their craters lying above the pre-eruption surface. These morphological distinctions are, however, often difficult and sometimes impossible to draw. Moreover, the depth-to-diameter ratios of the craters of maars and tuff-rings may be the same.

Most authors seem to imply that a tuff-cone has a relatively small crater within the top of a much larger cone, and hence the volume of inward-dipping ejecta is small compared to that of outward-dipping ejecta. In a tuff-ring, the volume of the crater is much larger relative to the volume of the surrounding pile of ejecta, and the diameter of the crater is also much larger relative to the basal diameter of the surrounding pile than is the case in tuff-cones.

Tuff-rings are generally believed to be formed almost entirely by the eruption of tephra, collapse playing at most a minor role. However, unconformities in the rims of tuff-rings in central Oregon and Iceland appear to have been produced by inward slumping of ejecta. Such unconformities may also indicate that the craters were enlarged, at least in part, by collapse, though the evidence is usually obliterated by the ejecta of later eruptions.

Some tuff-rings probably originated as maars the floors of which were then partly filled by later ejecta. The floor of the large, wide crater of Hverfjall in Iceland, for example, lies slightly above the level of the surrounding region, but only because late-stage eruptions and erosion partly filled a deeper maar.

Tuff-rings and tuff-cones, like maars, may contain central tephra-cones or lava lakes. Hverfjall provides an example of a nested tuff-ring, and there are several tuff-rings in central Oregon that contain lava lakes.

Diatremes

In 1891, Daubrée published the results of experiments he made in an effort to understand how volcanic pipes, such as those in Scotland and the Schwabian Alb of southern Germany, were formed. By means of artificial explosions, he drilled small, irregular holes through cylinders of various kinds of rocks, and to these perforations and the supposedly natural counterparts he gave the name diatremes. Slight modifications have taken place in the usage of the term since Daubrée's classic paper appeared. The 'Glossary of Geology and Related Sciences', published in 1957 by the American Geological Institute, for example, defines the term diatreme as follows: "A general term for a volcanic vent or pipe drilled through enclosing rocks (usually flat-lying sedimentary rocks) by the explosive energy of gas-charged magmas. The diamond-bearing kimberlite pipes of South Africa are diatremes".

Our own definition is the following: Diatremes are pipe-like structures filled with brecciated country rocks that are almost invariably admixed with juvenile, magmatic materials. They are formed chiefly by fluidized gas-solid systems that initially rise along fissures, joints, and newly opened fractures. Enlargement of these initial channels into approximately cylindrical pipes results from spalling and slumping of the walls, abrasion and comminution, and various kinds of subsidence. Diatremes that break through to the surface terminate in tuff-rings, tuff-cones, and maars. Activity commonly closes with the intrusion of magma as plugs and dikes, less commonly with discharge of lava.

Many of the Pliocene diatremes of the Hopi Buttes, Arizona, were

associated with maars in which fluviatile and lacustrine sediments accumulated, and some of the Miocene diatremes of the Schwabian Alb also ended in maars within which freshwater beds were deposited.

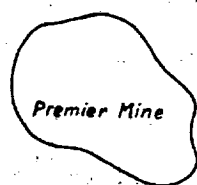
Studies of diatremes in Montana, Arizona, Scotland, and Palatinate, Germany, show that many are surrounded by ring faults, and that the fillings of some have subsided more than 1,000 m. Prior to subsidence, most of the diatremes were narrower than they are at present, and they terminated upward in tuff-rings, tuff-cones, and maars of type 'a' (page 7). Enlargement of the diatremes by subsidence also caused changes in the surficial structures. Close to the surface, the ring faults became inward-dipping slump-planes within the pyroclastic deposits, so that some tuff-rings and tuff-cones were converted into maars of type 'b' (page 7).

Diatremes vary in diameter from several tens of meters to more than 1,500 m. Their fillings may consist entirely of pyroclastic debris, both lithic and magmatic, but may also include large blocks and slices of country rocks that can be assigned readily to their original stratigraphic horizons.

Most diatremes reveal a crude, roughly concentric zoning of their pyroclastic fillings. They may be considered to be normally zoned if the central parts contain relatively large amounts of material carried up from deep levels, and the marginal parts contain larger amounts of material carried down from higher stratigraphic levels. Inversely zoned diatremes are quite exceptional, though two inversely zoned kimberlite pipes have been described from Siberia by Sibirtsev and Prokopchuck (1964), as mentioned in a review by Dawson (1968). Composite diatremes, consisting of a collar of kimberlite and a core of olivine melilitite have been

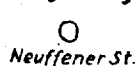
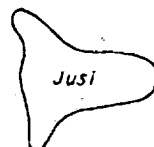
SOUTH AFRICA

kimberlites



JAKUTIA

kimberlites

SCHWÄBISCHE ALB
Mts.olivine
melilititesČESKÉ STŘEDOHŘÍ
Mts.olivine-bearing
alkaline basaltic rocks

2. Comparison of the sizes and outlines of diatreme outcrops from various countries (L. Kopecký 1966)

Fig. 1. Comparison of the sizes and outlines of diatreme outcrops from various countries. (after Kopecký, 1966).

described from Siberia by Ukhonov (1965).

Blind diatremes are those that never reached the surface.

Francis (1962) has presented an account of small 'incipient necks' from East Scotland that ended at shallow depths. They contain either relatively undisturbed sediments within a ring of breccia in which the blocks exhibit a kind of flow-banding parallel to the walls or they are filled completely with brecciated sediments of local origin which also display flow-banding near the margins. And Coe (1966), in his studies of intrusive tuffs in southwestern Ireland, found that parts of the original roofs are still preserved in contact with well-mixed pyroclastic debris containing exotic blocks (figure 2).

Bowes and Wright (1967) and Wright and Bowes (1968) have described breccia pipes from Scotland, some of which had no outlets large enough to allow coarse fragments to escape. Only fine material could have been carried away; the larger blocks, after being carried up, must have fallen through eddy currents at the margins of the pipes.

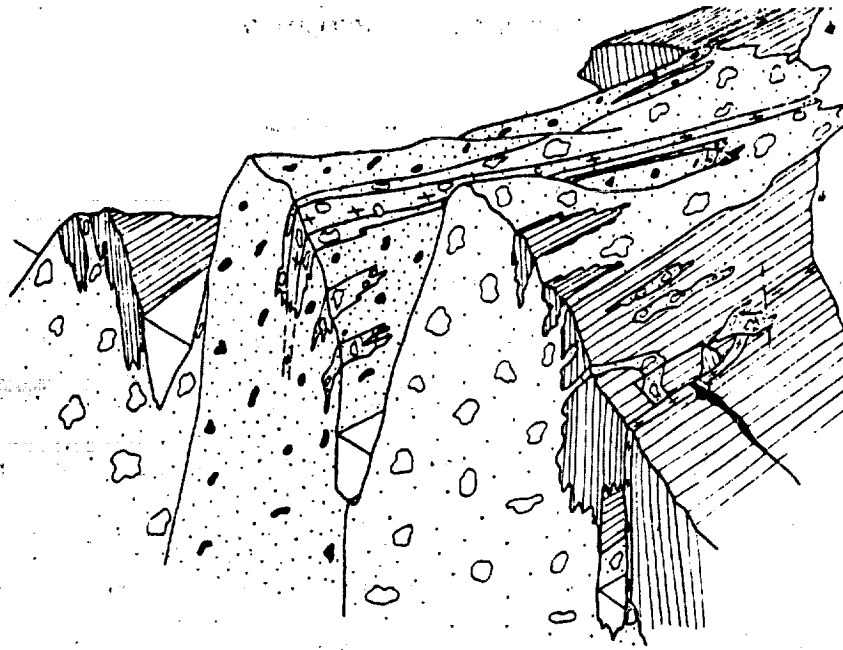


FIG. 8. Block-diagram of the relations at Black Ball Head. The ornament is the same as in Fig. 6 except that the sediments are ruled to indicate dip and strike.



FIG. 9. Grit block in tuffsite in contact with roof zone slates. Northern part of Black Ball Head.

Figure 2. Intrusive tuffs of Black Ball Head diatreme in contact with roof zone slates. From Coe, 1966.

Origin of Gas and Energy

The gas phase plays a major role in eruptions that produce maars, tuff-rings, and diatremes; nevertheless, little is known concerning the composition and mode of origin of the gases. The three principal sources have generally been postulated to be as follows: 1) Non-magmatic sources, chiefly water vapor generated by the heating of groundwater by rising magma; 2) Absorption by magma of water vapor, CO_2 , and other gases and their subsequent release; 3) Juvenile gases of purely magmatic origin. In most eruptions, the gases are probably derived from all three sources, but in widely different proportions.

Phreatic and Phreatomagmatic Eruptions

In all phreatic and in most phreatomagmatic eruptions, the gas phase consists predominantly of water vapor derived from groundwater. Phreatomagmatic eruptions produced the tuff-rings of central Oregon, Idaho, and Oahu, the Asotin pipes of the Columbia River plateau, and some of the maars in Iceland, and in each instance the eruptions took place where rising basaltic magma came in contact with abundant groundwater close to the surface, e.g. in lacustrine environments and near the shores of oceanic islands. Phreatomagmatic eruptions must also have been involved in the formation of many diatremes. Some diatremes in Scotland penetrated marine deposits and probably broke through to the sea-floor, and certainly many diatremes in the Hopi Buttes, Arizona, penetrated unconsolidated, water-soaked sediments to form maars within a Pliocene lake. Not only does the geological setting of many tuff-rings, maars, and diatremes make it reasonably certain that vaporization of copious groundwater was involved in their formation, but

so does the presence among the ejecta of abundant fragments of water-rich sideromelane, of accretionary lapilli, vesiculated tuffs, and well-developed impact pits such as are typically produced when ejected blocks fall into deposits of ash that are still wet.

The mechanism of phreatomagmatic eruptions can be evaluated with some degree of confidence, because it involves a number of observable relations that can be analysed quantitatively. The simplest case is that of an igneous body intruded at a depth of a few hundred meters in weak water-saturated sediments. The mechanics of intrusion of sills and their relations to phreatic eruptions have been examined by Bradley (1965), who has pointed out some of the relations between the depth of intrusion, the density of near surface rocks, and the role of vaporized water in the injection of sills. Although it is impossible to calculate the exact level of intrusion without a knowledge of the depth of origin of the magma and the weight of the entire column of crustal rocks, it is evident that a magma that is able to rise to summit vents that stand much higher than the regional elevation must also have sufficient hydrostatic and dynamic pressure to lift light sediments and will be intruded as sills wherever it passes from dense crustal rocks into basins filled with material lighter than the magma. Mudge (1968) has studied a number of examples of sills in which it is possible to determine the original depth of cover, and he found that most of the sills intruded layered sediments at depths of 3000 to 7000 feet. Sills that are responsible for phreatic eruptions must be somewhat shallower than this, because, as we shall see, the heat requirement of heating such a large vertical interval of wet sediments would demand an exceptionally thick sill.

When intrusions heat the water in overlying sediments to temperatures at which the system becomes unstable and erupts, a phreatomagmatic eruption ensues. Francis (1968) has shown that during Carboniferous time, extrusive volcanism in southern Scotland and central England changed to intrusive activity and phreatic eruptions as sedimentation of the Carboniferous beds added progressively thicker layers of light wet sediments. The relations revealed by mining of the Coal Measures are unusually complete. Francis (1959, 1961, 1967) has been able to correlate an individual vent with both the surface level at the time of eruption and the depth of an alkali dolerite sill that is believed to be responsible for the vent (figure 47).

The data supplied by Francis provide an opportunity to examine the thermal relations of a phreatomagmatic eruption produced by intrusion of a sill into wet sediments. Unfortunately, the thickness of the sill is still not known, but most of the observed sills in the district are less than 100 m. thick. The sill intrudes a sequence of sand, mud, and silt with a few seams of coal and limestone. Its original depth was about 600 m. below the surface of sedimentation. Owing to the interlayering of the sand and mud, circulation of water in the sediments was restricted by the low permeability of fine-grained layers. The original pore space of the sediments was undoubtedly high, perhaps between 10 and 50 percent.

The problem of temperature distributions in wet sediments intruded by sills has been examined by Jaeger (1959). He has shown that the maximum distance to which vaporization proceeds in the pore water of overlying sediments is of the order of the thickness of the sill, and under most conditions it is probably much less. Thus only a very thick or shallow

sill would produce a front of vaporized ground water that could approach the surface, and it is unlikely the phreatic eruptions will be triggered by this effect alone. This limitation is largely a consequence of the relatively large amount of heat required to vaporize the water. Much less heat is required to raise the temperature of ground water to its boiling point than to vaporize it, and, depending on the porosity and permeability of the sediments, water will tend to reach an equilibrium condition in which the temperature at any depth corresponds to the boiling curve as a function of pressure. Where convection can cause a rising current of water above the intrusion, the pressure gradient will depend on the rate of circulation and the permeability of the sediments. Under these conditions, the temperatures may exceed the normal boiling curve, especially below horizons of low permeability. Similarly, during heating of water-saturated sediments, water may be vaporized below relatively impermeable layers, but this will only be a transient condition, because the sediments are more permeable for steam than for liquid water, and the movement of water vapor will be accelerated until it again condenses. Condensation in cooler levels will add the heat of vaporization to the overlying horizon and subsequently increase the heat transfer, so that the effect of the impermeable layer is greatly reduced.

The end result of these heating processes is to bring the column of pore water in the sediments to its boiling temperature for the corresponding depth throughout the vertical distance from the surface to the heat source. How long it will take the sediments to reach this state will depend, of course, on many factors, such as water content, permeability, and the

thickness of the sill. Goguel (1953) has demonstrated that the accumulated energy stored in the sediments in the form of heat can be more than adequate to produce violent steam eruptions without further direct contributions from magmatic sources. Seldom are sufficient data available to calculate with any high degree of precision the energy required for the formation of an individual maar. White (1955) showed that heat stored in ground water was adequate to explain the 1951 eruption of mud and hot water from a thermal area in northern California. McBirney (1963), using data of Barrington and Kerr (1961), showed that a direct magmatic source of gases was inadequate to supply the energy requirements for formation of the Black Peak breccia pipe, but calculations of the potential energy of heated groundwater in the porous Navajo sandstone was more than adequate to perform the work involved in forming the pipe.

Diatreme Formation

The importance of phreatic or phreatomagmatic explosions cannot be questioned for those craters formed by shallow explosions through water-saturated sediments, but it is more difficult to evaluate the role of this mechanism in formation of deep breccia pipes or diatremes, especially when the surface features have long since been removed by erosion. Examples of breccia pipes that have never breached the surface and their similarity to pipes that can be related to surface explosions clearly demonstrate that at least two different mechanisms may be capable of boring through the crust and producing very similar features. A critical question to be resolved is the origin of the gases and energy that formed the pipe.

A small amount of groundwater may be present within the pores

and cracks of the wall rocks of a diatreme even at considerable depths. When such rocks are detached from the walls and become entrained and comminuted within the pipe, the water is absorbed in the magma, supplementing the magmatic gases, or it may even form a separate gas phase. Geochemical studies indicate that for more cases this water derived from the walls is probably the major constituent of volcanic gases and that it greatly outweighs the contribution of juvenile water from greater depths. Even at depths where there is little free water available, magma may gain water by dehydration of hydrous minerals, such as micas or amphiboles. It has also been suggested that if the wall-rocks are composed of limestone or marble, magma may absorb CO_2 and later release it as it rises to levels of lower pressure. The presence of veinlets and pellets of calcite and of pervasive, late-stage hydrothermal carbonates as a cement in the fillings of many diatremes that cut limestone beds in southern Germany has been taken as evidence of such magmatic absorption of CO_2 . Limestone assimilation was thought to be responsible for the calcium-rich and silica-deficient character of the melilite basanite found in the pipes and could also have contributed large volumes of CO_2 . Cloos (1941) and other later workers have shown that contamination by limestone of the wall rocks could not have been an important factor in the genesis of the magma, and isotopic and trace element compositions of most carbonates in such vents is distinct from that of limestones. This does not rule out the possibility that in a few instances CO_2 of sedimentary origin may have been important. Generation of CO_2 from marbles has been suggested by Coe's (1966) study of diatremes in southwest Ireland. No juvenile lapilli are to be seen among the pyroclastic

material in these pipes, but the fillings are cemented and veined by calcite, and calcite partly replaces many of the lithic fragments. Non-magmatic CO_2 may also be generated where diatremes cut through coal seams, as some do in Scotland, South Africa, Australia, and New Mexico; but in view of the fact that coal seams in the walls of these diatremes rarely show signs of coking, the amount of gas contributed from this source must be trivial.

Most large clusters of diatremes and many maars are related to the rise of alkaline ultramafic (kimberlitic) and carbonatite magmas rich in juvenile bases, notably H_2O and CO_2 . The fillings of the diatremes are usually rich in calcite, as veins and as cement, even in regions devoid of limestone and marble, and calcite may also be abundant among the pyroclastic ejecta, as in the carbonatite tuff-rings and maars of northern Tanzania (Dawson, 1964).

Liquid inclusions of juvenile CO_2 have recently been described by Roedder (1965) from olivine-bearing nodules and phenocrysts of alkali basalts, and in the olivine crystals of kimberlites, indicating the availability of CO_2 under extreme pressures at great depths. Kennedy and Nordlie (1968) therefore say that "exsolved CO_2 gas at pressures of more than 80,000 atmospheres might thus accumulate at great depth. Opening of fractures in the crust might then cause CO_2 to escape violently and to "sand-blast" its way toward the surface. The resulting channel might only stay open a few moments before plastic flow of rock closed it. During these few moments, pressures at depth in the earth's crust would be dropped and other pockets of gas along the channelway could detonate into the channel carrying with

them their load of fragmented rock". They also point out that thermodynamic calculations require "a partial pressure of carbon dioxide essentially equal to the confining pressure to have diamond crystals stable in an environment which contains substantial ferrous and some ferric iron."

Initial Breakthrough and Enlargement of Pipes

There is no general agreement on the mechanism by which breccia pipes penetrate great thicknesses of rock to erupt at the surface. Several geologists who have studied deeply eroded pipes in various parts of the world have concluded that 'highly energized' gases of deep-seated origin bored through the crust by a process similar to that proposed by Reynolds (1954). Shoemaker (1962) for example, suggested that the diatremes of the Hopi region of Arizona were bored from the mantle by gases which exsolved from monchiquite magma as it rose into fractured crustal rocks. Barrington and Kerr (1961) postulate that an intrusion crystallizing at some unknown depth under the Black Peak pipe near Cameron, Arizona, became progressively enriched in volatile components which ultimately exsolved from the magma and drilled their way through at least 2800 feet of sandstone and shale. Bowes and Wright (1961) described a roofed breccia pipe that was arrested in its rise to the surface and concluded that rapid crystallization triggered repeated explosions of exsolving gases which crushed the quartzite roof-rocks over the small intrusion. They deduce that oscillatory zoning of phenocrysts record the repeated explosions.

Many other examples of pipes could be listed for which an explosive origin has been proposed. In most cases, it has been suggested that gas at high temperatures and pressures moves upward through fractures and joints to erode a channelway to the surface. Starting with a small initial opening, the passageway is steadily enlarged by the growing volume and velocity of the gas stream. Although this mechanism has been widely advocated and seems to be supported by many observations, at least three serious

problems must be resolved before it can be accepted. First, an adequate source must be found for the large volumes of high pressure gas required. Second, the mechanics of flow of the gas through long narrow fractures needs to be explained. And third, an adequate source of energy must be found to brecciate and heat large volumes of cold rock without quenching the entire system. We shall consider each of these problems individually.

Most advocates of explosive boring of diatremes envisage a magmatic source of the gas. The problem of developing high vapor pressures and large volumes of gases from a slowly cooling magma has been pointed out on many occasions. Verhoogen (1949) has shown that there is no particular reason to believe that the vapor pressure of gases increases as magma cools, and he shows that under certain conditions gas pressure is more likely to decrease than to increase. Goranson (1937), Sosman (1950), Kennedy (1955) and others have pointed out that magma may become undersaturated as it rises from deep to shallow levels and is more likely to absorb water rather than exsolve it. Only at very shallow depths can lowering of pressure cause significant vesiculation, and even there the relative volumes of water vapor than can be exsolved from basaltic or rhyolitic magma, even under the most favorable conditions, can be shown to be very small at depths of more than a few hundred meters (McBirney, 1963). Shimazu (1961) has shown that it is impossible to accumulate large concentrations of a separate, high temperature gas phase at depth, because the diffusivity of gas is so great that the pressure will be dissipated much faster than a body of magma can cool and exsolve gas. Finally, a wealth of empirical data on underground explosions shows quite clearly that even if all the

foregoing calculations are erroneous and a highly efficient explosive mechanism comparable to a nuclear blast were conceivable, surface rupture is impossible if the focus of explosion has a depth of more than a few hundred meters (see, for example, Nordyke, 1961).

The penetration of streaming gas through thousands of meters of narrow fractures in cold rock presents additional problems. It is a characteristic of the flow of compressible gases, such as water vapor or CO_2 , that the pressure gradient along the path of flow is nonlinear. The gas will remain compressed and flow with a low velocity until it approaches the low pressure end of the conduit at which point it rapidly expands and accelerates. In steam wells, this acceleration takes place within two meters of the surface. It is unlikely, therefore, that high velocities can be attained by steam or volcanic gases as they rise through fractures and joints toward the surface. Their power to erode a channelway must be confined to a short interval very near the surface.

Finally, the heat-carrying capacity of the gas phase is so small compared to the high thermal inertia of the rocks into which it moves that it can have only a negligible heating effect. Even if exsolved from its source at magmatic temperatures, the effect of expansion will be to cool the gas adiabatically. In the Black Peak breccia pipe in Arizona, Barrington and Kerr (1961) postulated that the thermal alteration of sandstone around the pipe was the result of rising magmatic water. A simple calculation (McBirney, 1962) showed that the amount of water needed to accomplish this was measurable in hundreds of thousands of tons and if derived from a magmatic source, would require an immense body of molten rock. Many of the

hydrothermal effects observed in and around breccia pipes must be related to circulation of relatively low-temperature meteoric water, in many cases after the pipe is already formed. In order to provide a source for the mechanical and thermal energy consumed in forming a breccia pipe, a more efficient agent than water is needed to transfer large amounts of magmatic heat upward with the growing pipe.

Posed with these difficulties, one faces the problem of finding a plausible mechanism for the formation of deep breccia pipes, some of which have obviously risen through great vertical thicknesses of the crust in apparent defiance of all the obstacles just enumerated. One possible solution is an extension of the phreatomagmatic mechanism. An explosive eruption triggered at the surface by vaporization of heated groundwater, could be propagated downward as pressure is released on progressively deeper gas-charged horizons. A decompressional wave could theoretically extend to great depth and tap a source of magma which would rise into the pipe along with fragments of the walls from the entire vertical section.

Such a mechanism can reasonably be proposed for many modern explosion craters that were initially opened by phreatic eruptions but subsequently brought debris from considerable depth. Salt Lake Crater, near Honolulu, Oahu, is an excellent example. The crater was originally formed by a steam eruption produced when magma rose into water-saturated beach sands and coral, but as the eruption continued the focus of the explosions reached deeper and deeper levels bringing up fragments of ultramafic rocks and eclogites from depths well beneath the crust.

(Initial Breakthrough and Enlargement of Pipes)

There are other examples, however, where pipes show no evidence that the explosive activity was in any way controlled by surface features, such as groundwater. Instead, the pipes appear to have penetrated upward and broken out on the surface by some mechanism that was controlled by very deep conditions. The problem of interpreting this mechanism is aggravated by the fact that the structural features that are preserved and accessible for study are the combined products of a long and complex eruptive history, and evidence of the initial vent-forming process may long since have been destroyed by eruptions that followed the outbreak at the surface. For this reason, the importance of gaseous explosions in the pipe-forming process may tend to be exaggerated.

Studies of kimberlite and carbonatite pipes and other structures of great vertical extent have led some workers to conclude that they were formed by relatively non-violent processes that may have operated over a considerable period of time. The evidence for circulation of a fluidized system capable of separating and removing fragments of the roof and walls is very strong, but the temperatures that are indicated are commonly low and the fluid phase may well have been much denser than a normal gas. A dense hydrothermal system circulating by convection and pulsating with surges of pressure and relaxation may supply the heat and mechanical energy needed to form the pipe and at the same time provide a mechanism by which fragmental debris may be carried downward to be assimilated at deeper hotter levels.

Role of Fluidization

Fluidization in the present context refers to all processes in which denser particles are distributed within a rising liquid or gas phase. It thus covers gas-solid, gas-liquid, gas-liquid-solid, and liquid-solid systems. Here we are concerned mainly with fixed beds in which gas rises through particles at rest, with fluidized beds in which particles are

supported and agitated by gas, and finally with the domain of pneumatic transport in which particles are entrained in the gas flow.

Gas is generated at the eruptive source of a diatreme by exsolution, by contact with rocks containing a potential gas phase, or by both. This gas phase follows the pressure gradient which generally has a large vertical component. Most particles below a certain size will be incorporated in the gas stream and be carried upward or elutriated; however, some small particles will remain within the fluidized bed. Changes in pressure-gradients and gas velocities change the critical limits between the fields of fixed bed, fluidized bed, and pneumatic transport. Large fragments may be incorporated within the fluidized beds or in pneumatic transport if enough fine fragments are present; the effective density and velocity of the fluid phase supporting them are no longer the parameters of the gas phase but the density and velocity of the gas-small particle system.

Mixing of particles is a very important feature of fluidized beds and to a smaller extent of pneumatic transport. In many diatreme-fillings it may be so thorough that the materials are completely homogenized and fragments from many different stratigraphic levels come to lie next to each other. Mixing also leads to a systematic distribution of fragments with respect to size and spacing, larger fragments being more widely spaced than

smaller ones. This distribution results from the rise of a gas-bubble phase through a rather continuous gas-solid phase, as Davidson and Harrison (1962) have pointed out, for this causes any given particle to move at random through the bed. Particle movements in fluidized beds also increase thermal conductivity and accelerate chemical reactions between the gas and solid phases.

Mixing also leads to abrasion and grinding of the solid phase, so that angular fragments tend to become spherical. The resulting grain-size distribution of the main part of the size-range in diatremes resembles that of material comminuted in ball mills or by other mechanical impact-processes, as McGetchin (1966), Papenfuss (1963), and Weisskirchner (1967) have pointed out. Angular 'fines' produced by the process are incorporated in the gas flow and are carried upward. Blocks that enter the system but are too large to be fluidized must sink, and when they reach the bottom or margins of the pipe they become part of a fixed bed through which the gas phase continues to rise. Fluidization of smaller particles will also take place within the voids of the fixed bed, and will require the same linear gas velocity as the fluidization of small particles outside the fixed bed (Gabor, 1964). Fluidization in voids between large particles diminishes the amount of solids that mix. If a large subsiding block or a block of the fixed bed decreases in size, it may finally be entrained in the fluidized system or even be ejected.

Well-rounded blocks are commonly found in diatremes and among the ejecta of maars and tephra-rings. At the Hole-in-the-Ground maar in central Oregon, for example, some rounded blocks reach a maximum diameter

of 2.5 m., and in some of the diatremes of the Navajo country there are well-rounded blocks up to 4 m. across. It should be noted, however, that rounding may not be due solely to abrasion within the fluidized system but, as pointed out by McBirney (1959), may also result from thermal spalling.

The rate of flow in a volcanic vent changes with time, from the margin inward and from the bottom upward. At any specific place, therefore, a fixed or a fluidized bed may be formed, or pneumatic transport may take place. During formation of a diatreme, there is usually a fixed bed at the bottom and margins, a fluidized bed in voids and above the fixed beds, and pneumatic transport from the voids toward the surface. Fluidization takes place not only during the dying stages of diatreme formation, as Papenfuss (1963) has supposed; it is active during every phase of gas flow. Mature stages of fluidization, indicated by grain-size distribution, rounding of blocks, and homogenization of vent-contents, may be reached at the close of short-lived activity or during the main eruptive phase.

'Channeling' may occur in large pipes that display an inhomogeneous gas-flow distribution; indeed, the marginal parts may be devoid of gas flow. If some of the marginal parts are subsequently fluidized at depth, the entire collar may sink ('collar subsidence').

Counter currents may develop in pipes, especially in those with tapering walls. Close to the walls, where gas rises more slowly than it does in the center, granular materials may subside, then be picked up at depth, carried upward in the central parts, and subside once more near the margins. The effect on the vent-contents would be the same as if a fixed-bed collar sank at the margins and was picked up again at depth. Squires (1962)

has described such counter currents in experiments with large teeter beds, involving particles generally more than 0.25 mm. in diameter, where the walls of the container were carefully tapered. Zoned diatremes with features suggesting channeling, collar subsidence, and counter currents are to be seen in Arizona, Africa, Missouri, and Siberia.

When gas flow diminishes markedly or stops completely, defluidization takes place, the particles settling and the interstitial gas being pumped out by the action of gravity. Like fluidization, defluidization tends to result in a decrease in grain-size toward the top of the system.

If strong gas flow is renewed, it may cause 'plug flow' depending on the abundance and size of pores, and on the size and shape of the particles and of the vent itself. A mass of solid material is then transported on top of a large gas bubble, particles of different size within the 'plug' being carried upward at the same velocity. Near the surface, where the vent enlarges, the 'plug' may break apart, in which case the constituent particles then rise at different rates, small particles having nearly the same velocity as the gas phase, while larger fragments have increasingly lower velocities.

The gas velocity diminishes above the surface owing to increase in the volume of open spaces, which causes the pressure gradient to be reduced ultimately to zero, and also owing to mixing of cold air of low velocity. As a result, the solid phase loses support and falls out, large blocks starting their ballistic flight almost immediately. Small particles, requiring only small gas velocities to be supported, fall out later, and if there is no wind they fall almost vertically because of air drag. Such fallout may be considered a defluidization process.

Fluidization of liquid and solid materials by gas is also common within volcanic pipes. Among examples to which reference may be made are the pipes in southwest Germany described by Cloos (1941), Keller (1965), von Engelhardt (1965), and Weisskirchner (1967), pipes in Montana described by Hearn (1968) and those in Missouri described by Rust (1937). Rapid exsolution of a gas phase in these pipes sprayed the liquid phase (magma) and solid phase (phenocrysts and chips of wall-rocks) into open spaces above the magma, and the liquid was generally hot enough to coalesce around the solid particles to form free surfaces. Spinning of the ejecta in the gas phase and surface tension produced rounded and ovoid droplets of magma, most of them with a solid nucleus. Rotation also caused small crystals within the liquid to orient themselves tangentially with respect to the surfaces of the droplets, and occasionally rotation also produced equatorial flanges on the ovoid droplets. Fluidization of the droplets continued long enough to allow the surfaces to solidify before they came to rest; however, a few lapilli have indented crusts, indicating that the droplets were still plastic when they landed from flight.

Originally liquid lapilli (pellets) never have an eccentric core nor two cores, such forms being aerodynamically unstable. But unusually well-rounded lapilli that lack initially solid cores are present in a pipe on the south side of the Hohentwiel, in the Hegau district of southern Germany (Weisskirchner, 1967).

Liquid-solid fluidization must also occur within pipes at depths where temperatures are below and pressures are above those of the boiling curve of water. Such conditions should be present during an eruption at the

outer margin of the contact zone between intrusions and water-soaked wall-rocks, but no field evidence for such liquid-solid systems seems to have been described.

Velocities, Pressures, Temperatures, Densities, and Viscosities
of the Fluidized Systems

Very little is known about the quantitative values of the parameters of the two-phase systems that produce maars, tuff-rings, and diatremes, and about how they vary between the eruption-source and the surface; only crudely approximate values can be given.

The eruption-source, in other words the 'explosion focus' or place where the gas-phase originates either by exsolution from the magma or by contact of magma with water-bearing wall-rocks can generally be assumed to lie at depths of a few hundred to several thousand meters, though it is undoubtedly at very much greater depths in kimberlite pipes.

The temperature of the gas-phase at the eruption-source depends, of course, on how the gas originates and on the temperature of the magma involved. If the gas is produced by vaporization of groundwater, its temperature will usually be close to the boiling point curve, i.e. at several hundred degrees C. If the gas is juvenile, i.e. exsolved from magma, temperatures between about 800° C. and 1,200° C. can be expected. However, these temperatures fall rapidly as the rising gas heats the vent-walls and fragments incorporated from them. In addition, owing to decrease in pressure, the gas-phase expands and cools nearly adiabatically. Very low temperatures are indicated in kimberlite and alkali olivine basalt

pipes by the lack of coking of included fragments of coal, and by the absence of thermal alteration of fragments of shale that contain hydrocarbons which alter drastically when subjected to temperatures of only 200° to 300° C. (Kennedy and Nordlie, 1968; Wilshire, 1961). Hydration of olivine to serpentine also indicates temperatures below about 500° C. And the lack of uniform magnetization of the fillings of Siberian kimberlite pipes shows that temperatures were below the Curie point when the materials came to rest (Davidson, 1964). To what extent the magnetization in the Precambrian kimberlite of the Premier Mine, South Africa, is thermoremanent, indicating temperatures above 600° C., or chemical-remanent, indicating temperatures as low as 200° C., is uncertain (Jones, 1968).

Pressures at the orifice have been calculated by application of Bernoulli's theorem:

$$P = \frac{1}{2} \rho V_o^2$$

where ρ is the density of the ejected material and V_o the initial (muzzle) velocity at the crater. Minimum initial velocities are calculated using the formula for parabolic flight in vacuum and an ejection angle of 45°.

$$V_o = \sqrt{D \cdot g}$$

where D is the distance from the crater and g is the acceleration due to gravity. At the Hole-in-the-Ground maar in Central Oregon, blocks were found up to a maximum distance of 3,700 m. from the vent, indicating initial velocities of 191 m./sec. Since parabolic flight in a vacuum was assumed instead of ballistic flight, the initial velocities were probably more than 200 m./sec., corresponding to an orifice pressure of approximately

540 bars. Assuming an eruption-source 500 m. beneath the surface, the pressure at the eruption-source would be about 760 bars; indeed, if account is also taken of frictional effects, it would exceed 800 bars. During less violent eruptions at the Hole-in-the-Ground, the initial velocities were about 130 m./sec. and pressures at the orifice were about 230 bars.

Wentworth (1922) mentions that in some of the tuff-rings of Oahu, Hawaii, blocks 10 cm. across were thrown as far as 1.6 km., indicating an initial velocity of at least 125 m./sec. and an eruption-pressure of 212 bars. Gas velocities at depth are much smaller, and in some deep pipes it may well diminish to a few cm./sec.

The distribution of large blocks among the ejecta at the Hole-in-the-Ground suggests an apparent density of the fluid system of about 0.04 g./cm³. at the surface. At depth, where the velocities were much smaller and gas densities were much higher, the fluid density may have reached maximum values of approximately 2 g./cm³. Hence, most of the fine-grained materials occupy voids between the coarser fragments.

Viscosities of the two-phase systems under consideration are unknown. Murray (1967) gives values of 10 poises or less for the shear-viscosity of artificial fluidized systems, whereas Lewis (1968) cites values of around 10 centipoises. An even wider range must be expected in natural systems where other parameters also vary within wide limits.

Vertical and lateral variations of the gradients of all of the foregoing parameters are also virtually unknown. Some information concerning pressure-gradients has been obtained from studies of compressible gases flowing in long, narrow conduits. Pressure-gradients in such conduits are not linear from one end to the other; on the contrary, pressures drop

only slightly throughout most of the length, then fall rapidly close to the outlet as the gas accelerates. More than 80 per cent of the pressure-drop takes place within the last 10 per cent of the conduit. Measurements of pressure-distribution in steam wells 600 to 1,200 m. deep show that the greatest pressure-gradient lies within 1 to 2 m. of the surface (Fisher, 1955). It is not certain, however, if a similar pressure-regime obtains in volcanic pipes because the ratios of diameters to lengths are very different and so are wall-effects. In addition, internal frictional losses due to fluidization influence the pressure-gradient in diatremes. The pressure-drop in the two-phase system within a diatreme is higher than that of a one-phase (gas) system because the gas must perform work fluidizing the solid phase. Nevertheless, it can be assumed that the highest pressure-drop within a diatreme will be near the surface. It is largely for this reason that most of the large blocks are derived from near-surface levels where the gas-velocities are highest, whereas only small blocks are derived from great depths where the pressure-drop and gas velocities are small.

Flow-Banding

Flow-banding is a common feature in diatremes and in many pyroclastic sills and dikes. It was first described by Cloos (1941) who referred to it as Kettenschichtung (Chain-stratification) (figure 25, 26). It occurs generally close to the contact between homogeneous or unlayered pyroclastic debris and either wallrocks or large xenoliths; however it may be developed throughout narrow dikes and sills. It is expressed partly by variations in grain-size, the grains tending to increase in size away from the walls

and xenoliths. In addition, elongate fragments of country rocks or juvenile lapilli, and platy minerals, such as micas, are aligned parallel to the walls. Flow-banding in diatremes is usually restricted to zones less than 1 m. in width.

Flow-banding in pyroclastic rocks may be compared to flow-differentiation observed in liquid-solid systems. Bhattacharji (1964, 1967) explains such differentiation as the result of translatory and rotational forces exerted on solid particles by a liquid that flows along a wall and shows an increase in its velocity gradient away therefrom. His experiments show that for particles of equivalent shapes, the larger ones move away from the walls faster than the smaller ones; hence, the small particles are increasingly concentrated near the contact. Natural examples of such liquid-solid flow-differentiation are to be seen in some ultramafic and mafic dikes and sills.

Gas-solid systems behave in many respects like liquid-solid systems, and their fluid behavior can often be treated in almost the same way. In both kinds of systems, the solid phase is fluidized by a flowing medium, and when fluidized gas-solid systems flow along walls, the wall-effects are essentially similar to those in liquid-solid systems, modified only by the different fluid parameters of the transporting phase.

Wilshire (1961) has described layered pyroclastic materials in diatremes in New South Wales, and has suggested that the layering was caused by forceful injection of viscous, unfluidized aggregates into adjacent country rocks. Thin but extensive layers of different grain-size, many showing current features similar to cross-bedding, were formed, in his opinion, by differential rates of movement of adjacent layers. In our

opinion, however, flow-differentiation of solid grains cannot produce thin, extensive layers in the absence of a transporting liquid or gaseous medium; the layering described by Wilshire may be the result of subaerial deposition followed perhaps by subsidence.

Subsidence Processes

Various kinds of subsidence account for the presence within volcanic pipes of rocks that lie well below their original positions in the walls, among which the following may be mentioned.

'Fallback' of ejecta into open vents, and caving and slumping of the vent-walls may carry debris downward below their original levels, though these processes may be retarded by the rising fluid system when eruptive activity is strong. Farther down a pipe, large blocks will subside within the fluidized system when their terminal velocity is greater than that of the system; indeed some blocks may continue to subside when their terminal velocity is smaller, owing to internal random circulation. In large pipes with tapering walls the gas velocity near the center will be higher than it is close to the walls, so that counter currents will develop, particles near the walls sinking in the slowly rising gas stream to be entrained once more in the faster moving, central parts of the pipes.

During defluidization and when flow-rates diminish, large blocks subside more rapidly than small ones. Final compaction of a defluidized system will also carry blocks to lower levels, and most pipe-fillings develop saucer-shaped structures because their marginal parts lag behind

the central parts owing to frictional drag against the tapering vent-walls.

Channeling within a large vent may also lead to subsidence of still unconsolidated granular pyroclastic materials near the margins, and if the lower parts of the 'collar' are fluidized and carried upward, the overlying tuffs subside to take their place.

Withdrawal of magmatic support may result in caldera-like subsidences both of vent-fillings and of adjacent wall rocks, the walls themselves or newly formed cylindrical and conical fractures functioning as ring faults and the enclosed blocks sinking to produce saucer-shaped structures. The diameters of ring-faults may exceed 1.5 km. (Lorenz, 1967, 1968), and the surrounding wall rocks may be downdragged within a zone varying up to 60 m. in width, as around some of the kimberlitic pipes of Montana (Hearn, 1968).

The initial development of ring fractures is believed by Francis (1962) to take place during early stages in the formation of diatremes. This may well hold true for small pipes, but in our opinion the ring fractures that enclose large subsidence structures are produced at a late stage when a pronounced reduction of pressure is brought about by withdrawal of magmatic support.

Continued subsidence along a ring-fault may function as a kind of countercurrent if material is removed at depth from the 'collar' inside the fault and carried upward by the fluidized system. Such 'collar subsidence' may account for the extensive displacement of the fillings of pipes, such as those in Montana, which appear to have been fed from narrow dikes or thin sills rather than from large magma chambers into which overlying materials might have subsided. The amount of subsidence of a vent-filling

can only be determined if it took place within a ring-fault, and though the total amount of subsidence of an individual block within a vent may be determinable it will generally be impossible to evaluate the various processes involved in the displacement.

Extremely slow and long-continued subsidence of the fillings of some pipes takes place after eruptive activity has ceased, as in the case of some of the Hopi diatremes of Arizona where thick deposits of fluviatile and lacustrine origin accumulated within subsiding circular basins.

MORPHOLOGICAL FEATURES

Miscellaneous Surface Phenomena

Distribution of ejecta

Most eruptions are directed vertically or almost so, and the distribution of ejecta, particularly of fine ejecta, is controlled largely by the direction and velocity of the winds at various elevations during the eruptive episode. Among many other factors that influence the spread of ejecta are the muzzle velocities and angles of ejection of the fragments, the frequency distribution of grain-size, the density, size and shape of the particles, and the occurrence of rain. If the explosion foci lie deep in the eruptive conduit most of the ejecta rise almost vertically; if, on the other hand, the explosion foci are shallow there is much greater variation in the trajectories of the ejecta. During violent eruptions, ejecta tend to be dispersed over wide areas; during weak eruptions they tend to accumulate close to the source. The thickness of ejecta in the rims of some maars may be no more than a few meters, whereas in others it may exceed 100 meters. In tuff-rings and tuff-cones, the thickness of the ejecta is usually much more, commonly reaching several hundred meters; at the Koko Head tuff-cone on Oahu, for example, the ejecta reach a maximum thickness of 400 meters.

'Marginal eruptions' may issue from vents bordering maars, as in the Dreiser Weiher maar in the Eifel where four marginal vents developed around a subsided block of Devonian shales, and in the Rödern, a Permian diatrema in southwest Germany, where eruptions took place from a vent

at the margin of a later collapse-depression. Marginal eruptions, like central eruptions, may range from vertical to strongly inclined, and those that are inclined cause the ejecta to accumulate in fans (Wurffacher), the isopachs being markedly elongated in the direction of the blasts.

An example of inclined eruptions from a central vent may be examined at the Hole-in-the-Ground maar in Oregon. Many blasts were directed southeastward, as shown by the isopachs of the ejecta and the isopleths (lines of equal diameter) of large blocks. Large blocks are scarcely influenced by wind, whereas fine ejecta are strongly affected; hence a comparison of the isopleths of large blocks with the isopachs of the total ejecta of a given eruption may serve to distinguish between the effects of winds on the dispersal of ejecta from vertically directed blasts and the effects of inclined eruptions. If winds are strong during an eruption, the isopachs of the ejecta generally deviate much more from circles than do the isopleths.

Large blocks, being influenced only slightly by air-drag, start their ballistic flight the moment they escape from an eruption-cloud or when the velocity and density of the cloud rapidly diminish. The ballistic trajectory depends on the size and shape of the block, forming a curve with an impact angle greater than the ejection angle, and an ejection-distance shorter than that attained in parabolic flight in vacuum. The impact angle is relatively larger and the ejection-distance relatively shorter for small blocks than for large ones.

Most ejected blocks land within a few kilometers of the eruptive vent, their distance from the source depending mainly on the initial velocity and angle of ejection. At the Hole-in-the-Ground, blocks are distributed to a maximum distance of 3.7 km., which corresponds to an initial

velocity of about 200 m./sec. at an ejection angle of 45° . Blocks ejected with a velocity of 100 m./sec. reached a maximum distance of approximately 1 km.

Impact Pits

Blocks that fall on unconsolidated, fine-grained materials commonly produce impact pits. Those that fall on wet stratified deposits, such as are usually laid down during phreatic and phreatomagmatic eruptions, indent the beds to form so-called 'sags'; however, because of the plastic behavior of the moist deposits, the blocks do not disrupt the bedding. On the other hand, blocks that fall on dry deposits usually disrupt the bedding without producing sags.

Sags formed in subaerial deposits may or may not be symmetrical. Asymmetrical sags result from strongly inclined impacts; hence, the sides of the sags closest to the eruptive vents slope more gently than do the opposite slopes, and the latter may also display small-scale folding and thrusting.

If blocks fall into the sea or into lakes, they will only form asymmetrical sags if the water is very shallow. Below a certain water-depth, the blocks will sink vertically, and if they land with sufficient velocity to produce sags these will be symmetrical. An upward increase in the size of sags caused by the fallout of blocks during steam-blast eruptions through Laguna San Pedro, southeastern Guatemala, seems to testify to progressive rise of the stratified ejecta to shallower levels and final emergence above the lake during the course of the eruption (Williams, McBirney, and Dengo, 1964).

Accretionary Lapilli

Accretionary lapilli (volcanic pisolites) commonly form in the eruption-clouds associated with the development of maars, tuff-rings, and tuff-cones. Most of them measure between 1 mm. and 1 cm. in diameter, and consist of a core of lithic or juvenile material surrounded by one or many concentric or slightly eccentric layers of ash that generally becomes finer toward the rims. In many lapilli, the diameters of the ash particles in the outermost layers range from about 0.001 to 0.1 mm. (Moore and Peck, 1962).

Baerns (1966) has studied the effect of interparticle adhesive forces on the fluidization of fine particles, mostly less than 50 microns in diameter. He found that the adhesive forces are generally not due to electrostatic charges but to Van der Waals forces, especially to the attractive London component. In addition to the molecular forces originating from the solids, attraction between particles may also be caused by molecular forces exerted by absorbed fluids. And Squires (1962) says that fluidized beds operating in the 'sticky range' may be used to capture ultra-fine powders, with resultant onion-layer growth of particles. The same process is used commercially in the manufacture of cement.

Particles in the outer layers of accretionary lapilli in maars, tuff-rings and tuff-cones are generally too coarse to have been captured solely by Van der Waals forces; adhesion due to absorbed water is therefore considered to be the main cause of their formation. Where the lapilli accumulate in thick beds, as they do, for example, in the tuff-cones of the Menan Buttes in Idaho, they imply the condensation of unusually large

amounts of water vapor in the eruption-clouds. For that reason, thick beds of accretionary lapilli almost invariably result from phreatomagmatic eruptions, especially if they are associated with fragments of sideromelane, well-developed bedding, impact sags, and base-surge deposits.

Base-surge Deposits

The presence of cross-bedding and channel-structures in pyroclastic deposits has generally been attributed to erosional and aeolian processes. Recently, however, Moore (1967) has described these structures as a product of 'base surges' during an eruption of Taal volcano in the Philippine Islands. The effects of base surges have also been recognized by Fisher and Waters (1969) in their studies of current-structures at the Ubehebe Craters in Death Valley, California, and by Heiken (1970) in his studies of tuff-rings in central Oregon. When the directions of the currents responsible for the cross-bedding and channel-structures were examined, it was clear that the currents must have originated from the craters. Such radial patterns cannot have been of ordinary aeolian origin; they must have been the result of base surges.

Base-surge deposits may also be indicated by the presence on flattish ground of impact pits that are filled with coarse debris only on the side toward the crater. The horizontally spreading surge tends to drop coarse material on the onset side of each of the blocks in the impact pits because on that side the velocity of the surge is abruptly diminished. It must be noted, however, that on steep slopes, coarse debris may roll and slide downhill to accumulate against the upslope sides of blocks within

impact pits. Consequently, when examining ancient tuff deposits containing impact pits with blocks that are bordered on only one side by coarse debris, it is essential to know the original attitude of the deposits before it can be said that they were laid down by base surges.

Vesiculated Tuffs

Vesiculated tuffs--i.e. tuffs that contain vesicles between the grains--seem to have been described only from tuff-rings in Iceland (Einarsson, 1965; Murray, 1967). However, they are also present at Big Hole, Hole-in-the-Ground, and North Twin Lake in central Oregon (Lorenz, 1970). It must suffice to describe the vesiculated tuffs at Big Hole. Two hard layers are to be seen at Big Hole Butte, 2 km. from the crater. They are approximately 35 cm. apart, and each is about 3-10 cm. thick, interbedded with airfall and base-surge deposits. The beds immediately above and below the vesiculated tuff layers contain abundant accretionary lapilli, though few are present within the vesiculated tuffs themselves. The average size of the grains that compose the tuffs is less than 0.3 mm. Few of the vesicles exceeds 4 mm. in diameter, but some are up to 1 cm. across. They tend to be ovoid or spheroidal and have smooth walls lined with particles that are considerably finer-grained than most of those in the tuffs. Some vesicles are elongated and slightly inclined to the bedding, because of late-stage small-scale gravity-flow of the ash layers.

It is clear that the vesiculated tuffs just described are not airfall deposits because they extend at least 2 km. from the eruptive vent; at that distance from the source virtually all of the gas would have been separated from the ejecta before they were deposited. It seems far more likely that the tuffs were laid down by base surges in which the

transporting medium was expanding water vapor, much of which remained trapped within the wet, muddy tuffs even far from the vent. Continued expansion of the entrapped vapor produced the vesicles.

Slump Structures

Slump structures are common within the pyroclastic deposits of maars, tuff-rings, and tuff-cones. Convolution of the bedding, without disruption, results from the plastic behavior of the deposits while they are still water-soaked. Slump structures are therefore typical of the ejecta of many phreatomagmatic eruptions in which large volumes of water vapor are condensed to cause heavy rains. An excellent example is to be seen in the eastern rim of the Big Hole maar in central Oregon and well described by Heiken (1970).

Stratification

The pyroclastic deposits on the rims of maars, tuff-rings, and tuff-cones are generally well-bedded, and many are very finely bedded or even laminated. Individual beds range in thickness from a few millimeters to several meters. Dips usually conform to the angles of repose and hence to the inner and outer slopes, and they rarely exceed 35° . Mantle-bedding is characteristic, the layers being draped over the rims and slopes. Within many tuff-rings and tuff-cones, inward-dipping beds lie with strong unconformity on outward-dipping beds. At Hverfjall and Ludent in Iceland, the only beds that dip inward are those laid down by the final eruptions, and these took place following slumping or collapse of the earlier ejecta.

Inward-dipping deposits are unusual in the rims of maars, and they usually lie unconformably on older, outward-dipping deposits. Their

scarcity probably indicates that most of them disappeared, either by repeated enlargement of the crater by slumping and abrasion or by caldera-like collapse along ring-faults.

Origin of Bedded Tuffs Within Volcanic Pipes

Several explanations have been proposed to account for the presence of bedded tuffs within volcanic pipes, some of which are discussed below.

1. Inward-dipping tuffs may accumulate within a crater or the upper parts of the underlying conduit as a result of the 'fallback' of ejecta from successive eruptions. Marginal slumping, compaction of the ejecta, and withdrawal of magma at depth may then cause the bedded tuffs to subside within the pipe.

2. Heiken (1970) has suggested that during some phreatomagmatic eruptions, fine-grained, wet ejecta may be plastered against the walls of craters and pipes and adhere to them while new layers are being added. In his opinion, steeply dipping, vertical and even overturned layers with an aggregate thickness of more than 50 m. were formed in this way within some of the tuff-rings and pipes of central Oregon.

3. The bedded tuffs in many pipes owe their present position to subsidence. For instance, inward-dipping tuffs are to be seen within many pipes in Montana, Scotland, and southwest Germany, which are enclosed by ring-faults. In some of the Permian pipes of southwest Germany (Lorenz, 1967, 1968), tuffs that were deposited on a lava flow subsided together with underlying beds along a ring-fault and now lie 300 to 700 m. below their original position. Both the lava and the bedded tuffs dip inward,

but at diminishing angles toward the center of the pipe owing to frictional drag against the walls. Subsidence was accompanied by differential rotation of the bedding planes without extensive disruption of the bedding. In part, this may have been the result of slight rotational movements of individual grains in the unconsolidated deposits, and in part because of differential movements along newly formed radial and antithetic faults.

Francis (manuscript, 1969) has suggested that basaltic breccias and agglomerates in the centers of some pipes in Fife, Scotland, may have been emplaced by "diapiric effects" resulting from the reaction of rocks of varying competence to inwardly directed pressures induced by subsidence within downward-converging walls or ring-fractures. In the St. Monance pipe, basaltic magma seems to have been injected into fractures opened by diapiric movements related to subsidence. And Illies (1958) has described the diapiric rise of blocks of Keuper beds for distances of approximately 200 m. in a pipe in southwest Germany.

Thick deposits of inward-dipping tuffs can be seen at the surface in such tuff-rings as those of the Menan Buttes, Idaho, Diamond Head, Oahu, and those of central Oregon, where they accumulated unconformably on outward-dipping tuffs following slumping. Repeated eruptions alternating with subsidence account for the presence in the kimberlitic pipes of Montana of thick inward-dipping tuffs broken by unconformities and now found at depths of up to 1,280 m. below the original surface (Hearn, 1968). Subsidence of inward-dipping tuffs also took place in some of the pipes of Fife (Francis, 1967, 1969); in addition, outward-dipping tuffs that were presumably laid down on the outer flanks of cones are now to be found within the pipes, close to the marginal ring-faults.

Subsidence of bedded tuffs that were originally laid down sub-aerially but now occur at depths of 100 m. to more than 1 km. is indicated by the presence within pipes of such features as the following: 1, inter-bedded fluviatile and lacustrine sediments; 2, fossil wood; 3, beds of accretionary lapilli; 4, impact pits made by falling blocks and bombs; 5, structures formed by 'base surges'; 6, slices of country rocks derived from near the surface and now found at depth as collars surrounding bedded tuffs (Hearn, 1968) or still in undisturbed contact with bedded tuffs (Lorenz, 1967, 1968); 7, downdragged wall rocks; 8, saucer- and bowl-shaped attitudes of bedded tuffs bordered by ring-faults and showing steep marginal dips, accompanied locally by radial and antithetic faults.

Composition and Volumes of Pyroclastic Deposits

The magmas that provide the juvenile fraction of the fragmental deposits of diatremes, tuff-rings, and maars range in composition from ultramafic to rhyolitic, but the dominant magmas by far are ultramafic rocks and alkali-basalts. Among diatremes that contain ultramafic rocks are the kimberlite pipes of Africa, Siberia, and Montana; among those containing alkali-basalts are those of the Eifel and Schwabian Alb in Germany, and those of Czechoslovakia, Scotland, New South Wales, and Arizona. The tuff-rings of Oahu also consist mainly of alkali-basaltic ejecta. At the other extreme are rhyolitic pipes such as those in Nevada (Gates, 1959). In the small cluster of Permian diatremes in southwest Germany, the magma-types range in composition from high-alumina quartz tholeiite to rhyodacite (Lorenz, 1968).

Most diatremes, maars, and tuff-rings not related to ultramafic or alkali-basaltic magmas are associated with tholeiitic basalts and are of phreatomagmatic origin, e.g. some Icelandic maars and tuff-rings, and the Asotin pipes in the Columbia River Plateau (Fuller, 1928). Such pipes, maars, and tuff-rings usually occur singly or in small groups; they form large clusters only where abundant groundwater is present over an extensive area.

The amount of juvenile, magmatic material among the pyroclastic ejecta may range from close to zero to almost 100 per cent. However, most tuff-rings consist predominantly of juvenile material, accidental, lithic debris normally making up less than 30 per cent of the total ejecta. Examples in which the content of lithic debris is unusually high are the maars Hole-in-the-Ground, Oregon, and Viti, Iceland. The relative paucity of lithic debris in most tuff-rings suggests that the underlying conduits are either short or narrow or both, and the paucity of lithic debris around maars suggests that they must have been produced in part by subsidence along ring fractures.

Study of lithic debris erupted from maars and tuff-rings and that found inside diatremes shows that fragments carried upward from deep levels are generally less abundant, smaller, and more rounded than those derived from higher levels. One reason is that fluid velocities at depth are smaller and are generally insufficient to transport large blocks; in addition, fragments uplifted from great depths tend to be entrained in the fluidized system for longer periods than those entrained closer to the surface, and hence they tend to be more abraded, polished, and rounded.

The volume of ejecta associated with a maar, tuff-ring or tuff-cone very rarely exceeds 0.5 km^3 . Diamond Head on Oahu, one of the world's largest tuff-rings, has a volume of approximately 0.6 km^3 ; the volume of ejecta blown out by the steam-blast eruption in the Soeh Sink, Sumatra was 0.21 km^3 ; and Thorarinsson (1960) calculated that the volume of debris thrown out to form the tuff-ring of Hverfjall and the surrounding layer of tephra was about 0.5 km^3 . At the Hole-in-the-Ground maar in central Oregon, the volume of ejecta at the surface was approximately 0.125 km^3 or $2.5 \times 10^{14} \text{ g}$. The Nilahue maar in Chile erupted 0.4206 km^3 of ejecta consisting mostly of basaltic scoria, and the volume of scoria, when recalculated as magma and added to that of the lithic debris, was almost the same as that of the crater (0.1784 km^3).

The volume of material discharged during the formation of maars may range from about three times to one-tenth of the volume of the crater, the ratios depending partly on density contrasts between the original country rocks and magma on the one hand and the pyroclastic debris on the other, and partly on the amount of subsidence of the conduit-fillings and adjacent walls.

In addition to the ejecta deposited outside the vents to form the tuff-rings and cones, large volumes of debris remain within the feeding conduits. If, for example, one assumes a conical pipe with a point-source at a depth of 2 km. and a surface diameter of 0.5 km., the volume within the pipe approximates 0.13 km^3 ; or if one assumes a cylindrical diatreme 0.5 km. in diameter and 1 km. deep, its volume is about 0.2 km^3 . At the Hole-in-the-Ground maar in central Oregon, the pyroclastic debris below the floor of the crater was estimated by means of drill-holes and other evidence to be about 0.1 km^3 .

(Composition and Volumes...)

This amount, added to that of the ejecta deposited at the surface, makes a total volume of approximately 0.225 km^3 .

Vent Intrusions and Extrusions

Magmatic intrusions may form a large or small part of a diatreme. They may occupy so much of the volume that only small patches or a thin collar of pyroclastic debris remain to indicate the early explosive stage of development; on the other hand, intrusions may be restricted to a few thin dikelets.

Most magmatic intrusions have the form of thin, irregular, branching and steeply dipping dikes or small plugs that cut across the pyroclastic debris and across large blocks of country rocks that have slumped into the diatremes from the walls. Radial dikes are rarely present within diatremes but they commonly extend outward from the walls, as in the Ship Rock diatreme in the Navajo country. A few diatremes are partly surrounded by arcuate dikes (cone sheets) that cut the wall-rocks, and in some of the kimberlite pipes of Montana, the pyroclastic fillings are partly or entirely surrounded by dikes of peridotite, from about 0.5 to 1 m. wide, that were intruded along ring faults.

Study of columnar joints in basalts occupying Carboniferous vents in western Scotland shows that many intrusions are sills intruded into bedded tuffs (White, 1968). Sills are also present in some of the diatremes of the Navajo-Hopi country. The attitudes of pipe-vesicles and the orientation of minerals may assist in determining the shapes of intrusions and the directions of flowage where exposures are poor.

If magma issues from the top of a diatreme it may form a lava lake within a crater or maar, as in the tuff-rings of central Oregon (Peterson, 1963; Heiken, 1970), or it may overflow to produce widespread sheets as in the Hopi Buttes, Arizona (Williams, 1936), and the Permian Birnberg pipe of Palatinate, southwest Germany (Lorenz, 1968). In the large Ben Hiant vent of Ardnamurchan, Scotland, pitchstone lavas alternate with bedded pyroclastic deposits (Richey, 1938, 1961). Erosion of the soft pyroclastic materials of tuff-rings that once contained lava lakes produces mesas such as Flat Top, Table Mountain, and Table Rock in central Oregon. Occasionally, cinder cones may develop within tuff-rings or maars, as in the Zuni Salt Lake of New Mexico.

Intrusion and extrusion of magma may take place before or after the contents of a diatreme and the adjacent wall-rocks subside. Intrusion prior to subsidence may be indicated by the presence of blocks of intrusive rocks within bedded tuffs that can be shown to lie below the levels at which they were deposited; it may also be indicated by the brecciated and slickensided margins of intrusions adjacent to ring faults, and by the displacement of intrusions along such faults.

Intrusions following subsidence may be indicated by dikes that cut or are intruded along ring faults, or by dikes injected into expansion-fractures created by diapiric movements in tuffs that have subsided. In the Permian Birnberg pipes of southwest Germany, a crater produced by subsidence was later occupied by a lake of lava (Lorenz, 1968).

The walls and fillings of diatremes may also be intruded by gas-solid, fluidized systems within which the solid materials may be of

magmatic or accidental origin or a mixture of both. Some of the plugs, dikes, and sills of intruded pyroclastic debris display flow-banding such as may be seen, for example, in the diatremes of Scotland and Montana.

Shapes of Feeding Chambers

Clusters of volcanic pipes are commonly assumed to have been fed from sills or laccoliths intruded at rather shallow depths. For instance, the feeding chamber of the 335 pipes of the Schwabian Alb was a sheetlike body extending over an area of more than $1,600 \text{ km}^2$ at a depth of more than 1,600 m., and the major diameters of the pipes generally follow lines of structural weakness in the roofrocks.

Rittmann (1954) and Tosson (1954) have described a series of diatremes in Egypt that were formed by phreatomagmatic eruptions when a sill intruded shallow, water-saturated rocks. And Francis (1967, 1968) has shown that some pipes in Fife, Scotland, and Nottinghamshire, England, were fed by sills of alkaline dolerite with a maximum thickness of approximately 50 m. A sill that fed some of the pipes in Fife was intruded at depths of less than 600 m. below the surface.

On the other hand, many diatremes are known to pass downward into dikes. For instance, mining shows that the outlines of the kimberlite pipes of South Africa become increasingly elongate and finally become dikelike at depth. The Roberts-Victor Mine, and the Kimberly and St. Augustine pipes, which lie on the same dike, provide illustrations (figure 3).

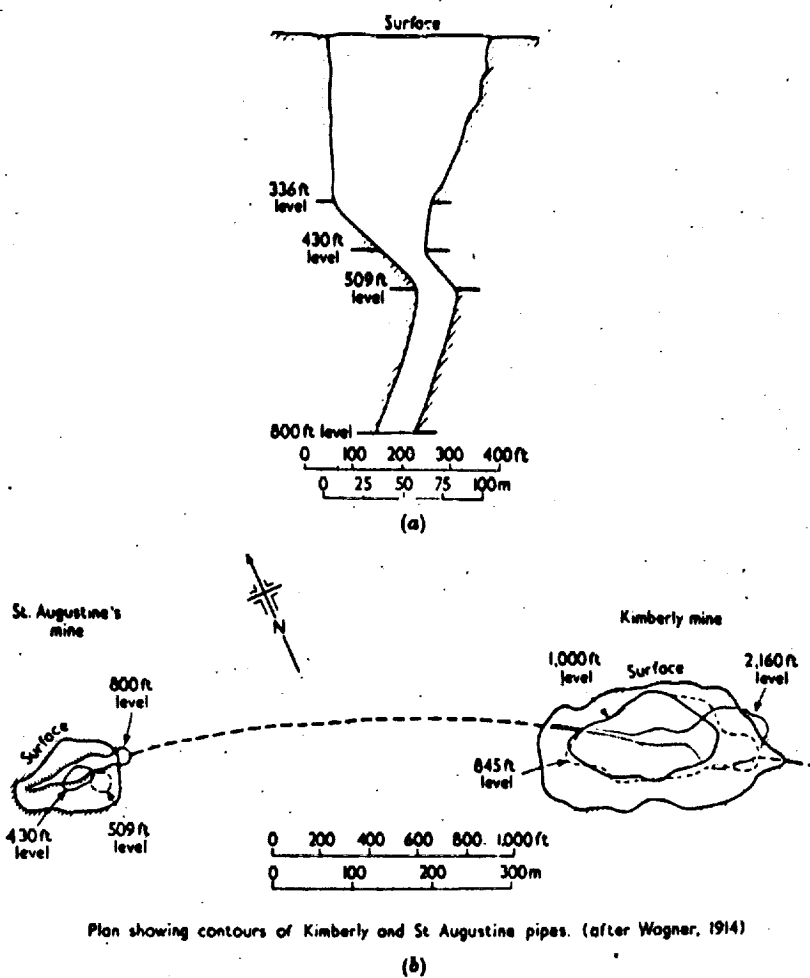


FIG. 2. St. Augustine's and Kimberley Mines, South Africa. (a) Section through St. Augustine's pipe in a northwest direction (after Wagner, 1914). (b) Plan showing contours of Kimberley and St. Augustine pipes (after Wagner, 1914).

Fig. 3 St. Augustine's and Kimberley diatremes, South Africa. (after Wagner, 1914).

(Shapes of Feeding Chambers)

Many pipes in the Hopi Buttes, Arizona, lie on northwest-southeast lines, parallel to adjacent dikes (Williams, 1936; Hack, 1942), and in Shoemaker's opinion (1962) these lines reflect the trend of fractures in the Precambrian basement along which magmas rose to the surface. The Red Mesa diatreme in the Navajo Reservation of northern Arizona is merely a local enlargement of a dike 2 km. long, composed of serpentine tuff. The Moses Rock breccia dike in the same area is exposed over a length of more than 7 km., with a maximum width of about 300 m. However, energy release was far from uniform over the full length of the dike; on the contrary, it was concentrated at a few restricted parts, thus giving rise to pipe-like bodies that presumably terminated in maars approximately 1 km. above the present erosion-level.

The Permian pipes of southwest Germany cluster around a younger intrusive dome of rhyolite. Pipes close to the dome contain intrusions of intermediate to acid composition, whereas the slightly older pipes farther from the dome are basaltic. These relationships suggest that both the pipes and dome were fed from a common magma chamber that supplied increasingly siliceous magmas as activity progressed, and presumably the shape of the chamber was irregular or roughly laccolithic. But since the major diameters of the pipes follow the two principal tectonic trends of the region, it may be supposed that the pipes were fed by dikes aligned along joints and fissures in the roof above the magma chamber.

The kimberlitic diatremes of Montana (Hearn, 1968) are distributed within a broad zone 160 km. long, at both ends of which there are partly brecciated dikes, suggesting that the diatremes themselves extend

(Shapes of Feeding Chambers)

downward into a dike-swarm. Maars and tephra-rings in Iceland are characteristically related to fissure-eruptions, and the tephra-rings at Mud Lake, Idaho, were also fed from fissures.

Maars in the Eifel cut folded Devonian shales and are arranged in a strip 50 km. long, at the intersection of two structural elements. This long strip of maars is almost surely alined along a fissure-system. The Meerfelder Maar, for example, lies at the end of a volcanic chain in which activity migrated northwestward, and the longest diameter of the maar trends in the same direction.

It should be noted in conclusion that the major diameter of the Hole-in-Ground maar in central Oregon trends northwest-southeast, parallel to one of the two main structural trends of the region. Moreover, most of the eruptions that produced the maar were inclined toward the southeast, and geophysical measurements within the crater reveal the same trend. There can be little doubt, therefore, that the Hole-in-the-Ground was formed by magma that rose along a fissure.

Part II. Examples of Maars, Tuff-rings, and Diatremes

Historical Examples of Maar-Formation

(Stehn 1934; Müller and Veyl 1956; Illies 1959)

A striking example of a maar-forming historic phreatomagmatic eruption is that of Nilahue, Chile, described by Müller and Veyl (1956). Following several local earthquakes, a vent opened on July 27, 1955 in the valley of the Nilahue River, on the western slopes of the Andes. Ash-laden clouds rose to heights of 7,000 m., causing almost total darkness over an area 20 km. across. About 17.5 per cent of the ejecta consisted of fragments of old rocks, mainly basic lavas and metamorphic and plutonic rocks. By far the major part of the ejecta consisted of basaltic scoria, though a few lumps of siliceous white pumice were also found.

At first, individual eruptions lasted from 20 to 30 minutes, with quiet intervals of approximately 30 minutes; later, the eruptions lasted for an hour or so, and their frequency diminished. During the first two days, eruptions took place from a fissure, but on the fifth day, two distinct craters could be recognised. By the tenth day, the two craters had merged into one, into which a stream poured to form lakes during quiet intervals. Activity declined rapidly after the fifth day, but isolated weak eruptions continued at irregular intervals for another three months.

The volume of the final crater, approximately 0.18 km^3 , was found to be almost the same as that of the ejecta (0.42 km^3 .) when the scoriaceous fragments were recalculated as magma and their volume was added to that of the lithic debris. According to Illies (1959), the crater was enlarged in part by slumping of the walls. The dominant winds were blowing to the west, in which direction, the thickness of

the ejecta 12 km. from the source was 60 cm.; 20 km. away, it was 10 cm., and 120 km. away it was only 1 mm.

Müller and Veyl thought that the volume of the crater could only be accounted for by assuming that country rock had been fused by hot gases to produce the scoria. Admittedly, the white siliceous pumice may have been formed by melting plutonic basement-rocks, but very much higher temperatures would have been required to produce the basic scoria by melting basic rocks. It is much more likely that the scoria were derived from juvenile magma, and that the pit was formed in large part by collapse of old rocks into the space evacuated by the basaltic magma. Activity seems to have been triggered by a phreatic eruption caused by vaporization of groundwater in the river-sediments, possibly when a basaltic dike was intruded along a north-trending fissure. Once begun, the eruption was propagated downward rapidly until the intrusive magma was tapped to supply the bulk of the ejecta. Rapid evisceration of the magma then led to collapse. The magma-level cannot have been more than a few hundred meters below the surface.

An excellent example of a steam-blast (phreatic) eruption is that of Pematang Bata which produced maars in the Soeoh Sink, Sumatra, in 1933 (Stehn, 1934). The Semangka River enters the wide, alluviated structural depression from the north, then disappears by seepage through the porous sediments to reappear in a swampy area at the opposite side of the sink. Small hot springs and fumaroles have been present within the sink for a long time, and many craters mark the sites of previous eruptions. On June 27, following a strong earthquake that was felt throughout southern Sumatra and northern Java, a marked increase was

noticed in the pressure and volume of steam given off by fumaroles over a broad area within the Soeoh Sink. The activity continued to increase until, 10 days later, two craters were opened by strong steamblast eruptions of sand and mud. The craters were nearly circular, one measuring 2 by 1.5 km., and the other 1 by 0.75 km. across. By July 16, a zone 5 km. long and 1.5 km. wide was in violent eruption. Debris was spread over an area of 35 km^2 , its volume amounting to $2.1 \times 10^8 \text{ m}^3$. No fresh magma was discharged. The depth of the explosion foci was estimated by Stehn to have been approximately 270 m. beneath the surface, within the water-saturated alluvium.

Other examples of historic phreatomagmatic eruptions leading to the formation of maars include the 1824 eruption of Viti in Iceland (page 73), the 1886 eruption of Tarawera, New Zealand (Thomas, 1888), the 1907 eruption of the Shtjibel maar in the Ksudack caldera, Kamchatka (Vlodavetz and Piip, 1959; Steinberg, 1965).

Maars in the Eifel, Germany

(Frechen 1962)

(Noll 1967)

A suite of carbonate-rich alkali basalts--leucitites, nephelinites and intermediate types--occurs in the western part of the Eifel district, in a large variety of volcanic forms such as tephra cones, lava flows, and maars. Volcanism began in early Quaternary time and ended less than 10,000 years ago. It was related to a flexure and deep-seated linear structure and was strongest where these structures cross. The maars generally lie outside the area of most intense activity in a strip, 50 km. long, between Bad Bertrich and Ormont. They erupted toward the end of the volcanic episode between 12,500 and less than 10,000 years ago.

CO₂ springs are common in the West Eifel but are rare in the area of maars, a fact which has been taken as evidence for intense degassing during the explosive activity. CO₂ certainly formed a major component of the gases responsible for the eruptions. Although many maars lie in valleys, the area seems to have been unfavorable for phreatic activity because the country-rocks consist of Devonian shale of very low permeability (Noll 1966, in Ollier 1967).

The thirty maars are funnel-shaped or basin-like with flat floors. Some are wide and shallow. Their diameters vary between 60 and 1500 m., their depths between 5 and 180 m., and the depth-to-diameter ratio is between 1:3.6 and 1:23. The original depths are usually not determinable because of later infill and because some maars formed in valleys or along their sides. Many are filled with lakes, the local name for which, Maar, has been long used for volcanic landforms of this type.

Maars in the Eifel, Germany

Most of the pyroclastic deposits are well-bedded and consist mainly of angular to rounded fragments of Devonian rocks in a fine-grained matrix of sedimentary material. In addition, juvenile lapilli, single crystals and blocks of alkali basalt and ultrabasic rocks are common. The latter consist of dunite, peridotite, hornblendite, and biotitite (Frechen 1948, 1962, 1963). A few maars erupted mainly juvenile material.

With few exceptions, the pyroclastic deposits occur as thin sheets that form low rims. At some maars, however, one or more pyroclastic fans can be recognized on the side of the crater; these may indicate directed blasts.

Several types of maars can be distinguished:

- 1) True maars formed by gas eruptions. Some subsidence of blocks within the pipe is probable because the volumes of the maars are generally larger than the volumes of the ejecta. Ratios of depth to diameter are about 1:8. Some maars are independent of other volcanoes.
- 2) Subsidence basins formed by collapse of large blocks of country rock along arcuate faults. Marginal, directed blasts issued from the inward-dipping faults. The volumes of the basins greatly exceed those of the ejecta. The ratio of depth to diameter varies between 1 to 13 and 1 to 20. Some basins were formed by withdrawal of magma consequent upon eruptions elsewhere in the area; in other cases the withdrawal has no apparent relation to nearby volcanoes.
- 3) Kesseltümler are round basin-like depressions in which no ejecta have yet been found. No definite proof of their volcanic origin has been presented.

Maars in the Eifel, Germany

Dust-layers at the base of the ejecta indicate that the initial eruptions were weak. Gases rising along joints blew out very fine lithic dust. The overlying coarser deposits contain increasing amounts of juvenile material and suggest increasing diameters of the vents and craters. A sequence of different layers resulted from pulses of activity similar to those observed in Chile in 1955 during formation of the Nilahue maar. The composition and sequence of layers and the roundness of blocks and lapilli indicate mechanical processes such as fluidization and elutriation at different levels within the pipes.

The magma chambers beneath the maars lie at a depth of several thousand meters, near the top of the metamorphic basement, as indicated by the occurrence of metasomatically altered metamorphic fragments and juvenile biotites and hornblendes formed at a considerable H_2O partial pressure. Disruption of the magma and gaseous transport of solid material began at much shallower depths.

The basin of the Dreiser Weiher measures 1360 by 1180 m. across and 36 to 120 m. deep below the top of the Devonian country rock. Four pyroclastic fans can be recognized corresponding to four directed blasts, each from a different vent near the margin of the basin. Geomagnetic measurements (Cipa 1955) show the sources as positive anomalies.

Although all four pyroclastic fans were formed by eruptions from different vents, the nature of the ejecta and their sequence indicate a derivation from a single magma chamber. Ejecta in successive fans show an increasing fayalite content of olivine, and systematic variations in the content of Ti, Cr, Fe^{2+} , Fe^{3+} , and Mg in the pyroxenes and hornblendes.

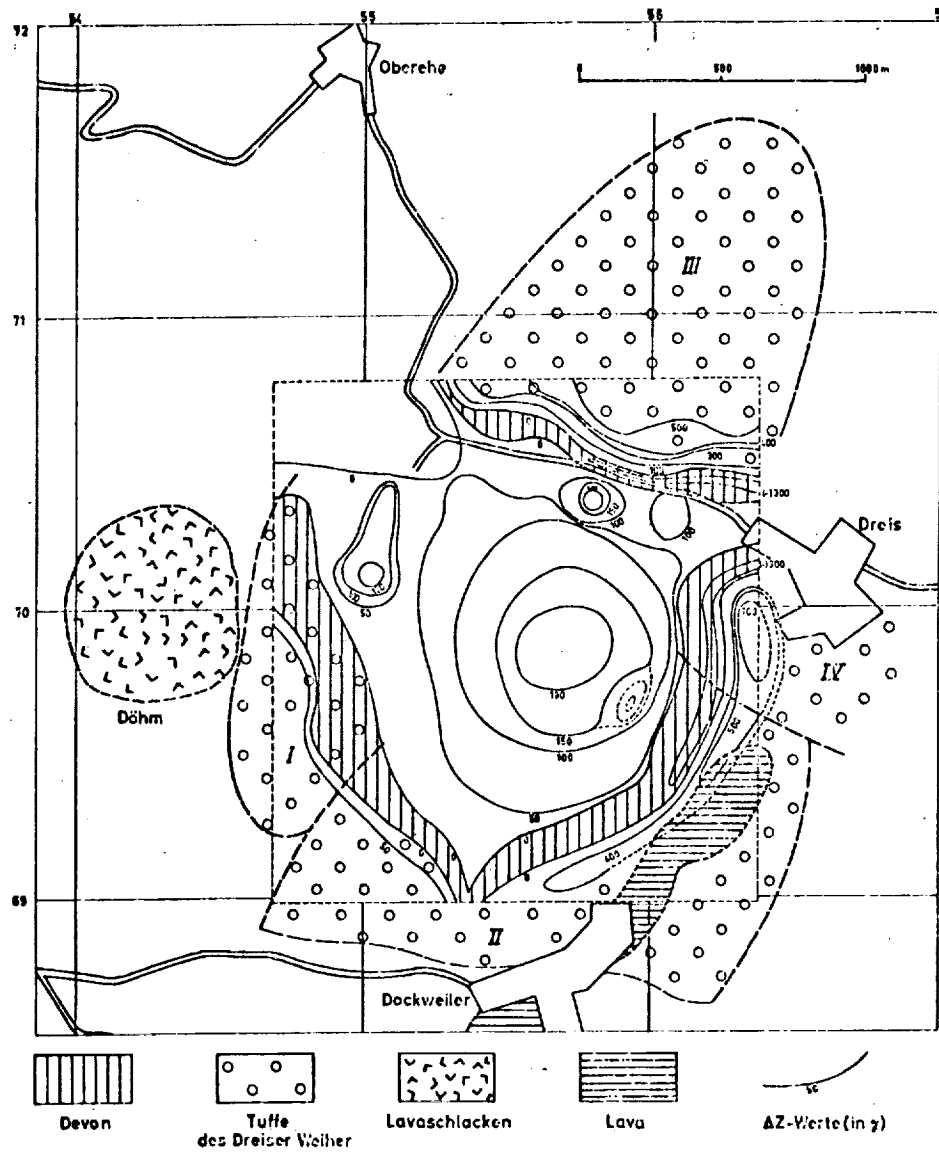


Figure 4 . Volcanologic-geomagnetic map of the Dreiser Weiher; is-anomalies from Cipa, 1955. From Frechen, 1963.

Maars in the Eifel, Germany

A study by Aoki and Kushiro (1968) of the clinopyroxenes found in ultrabasic nodules, indicates that they crystallised from alkali basalt magma and formed cumulates in the volcanic conduit. However, the lherzolite fragments may have been derived from the upper mantle.

The fact that the volume of the pyroclastic deposits is much less than that of the basin indicates subsidence of a central block. Drill-holes near the center revealed Devonian rocks under a thin pyroclastic cover.

Maars near Daun. The Gemündener Maar is 560 by 675 m. in diameter and 53 to 154 m. deep. Ejecta fans extend toward the northwest, northeast and southeast, their contents indicating progressive enlargement of both the pipe and crater during the course of the eruption. The Weinfelder Maar is 575 by 625 m. in diameter and 67 to 87 m. deep. The Schalkenmehrener Maar consists of two craters, the western one being younger and slightly larger. All three of these maars were fed by magma containing the same types of ultramafic nodules and separate minerals. They were formed between 11,000 and 10,500 years ago.

The maar at Meerfeld lies at the northwest end of a volcanic group. Activity migrated northwestward, starting with ejection of scoria and outpouring of a lava flow and ending with the formation of the maar, which is slightly elongated in a northwest direction, and measures 1200 by 1480 m. in diameter, and is 113 to 212 m. deep. Ejecta-fans spread to the southeast and west, and the walls of the maar on those sides show grooves formed by the abrasive action of the inclined blasts.

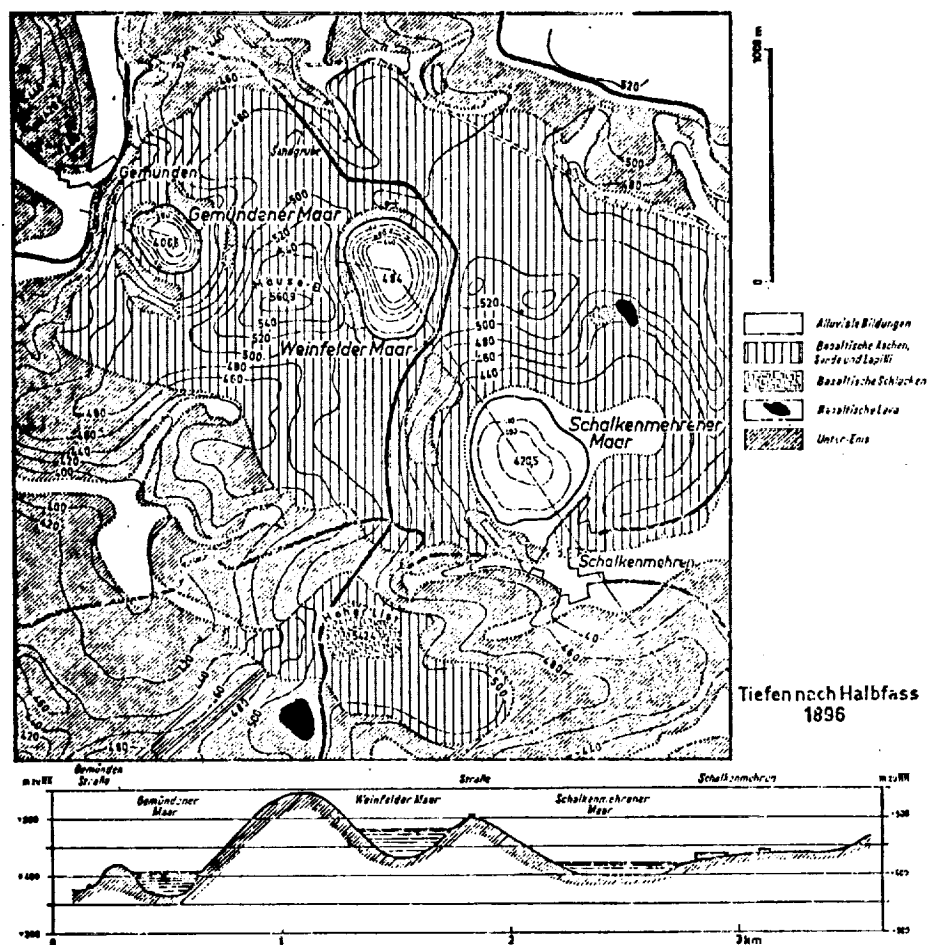


Figure 5. Maar group at Daun, Eifel. From Schulte, 1891, 1893.

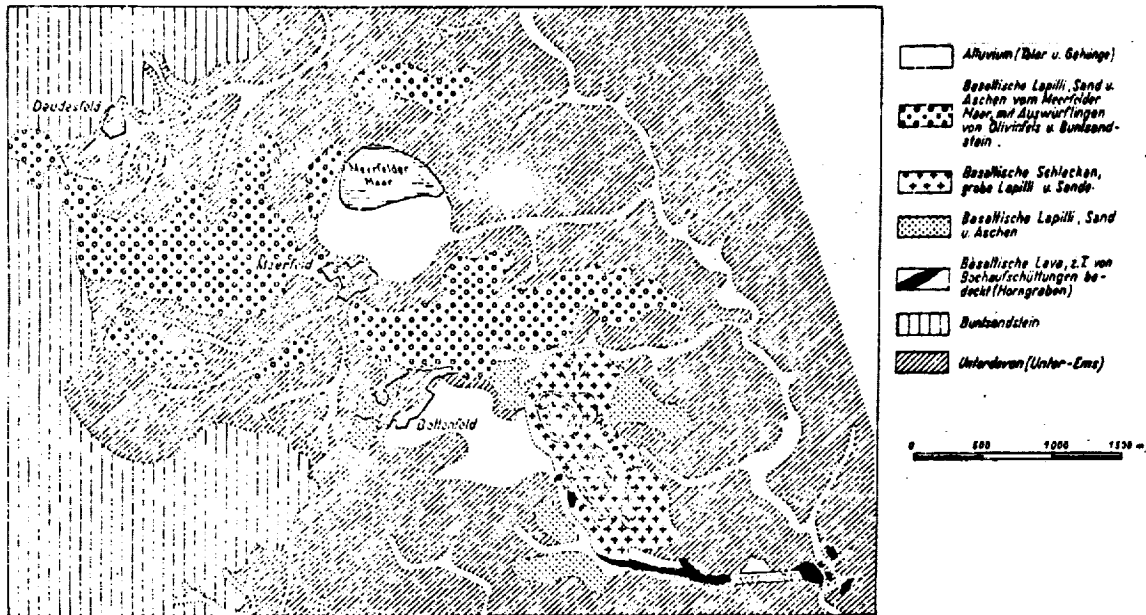


Figure 6. Geologic map of the Mosenberg area and the Moerfelder Maar.

From Ahrers, 1922.

Maars in the Eifel, Germany

The Pulvermaar was formed in a valley and is nearly circular with a diameter of 800 to 900 m. and an average depth of about 124 m. The pyroclastic ejecta in the rim are up to 10 m. thick and were deposited by central eruptions. A weak eruption near the northern wall was directed toward the northwest and a small lava plug near the lower south wall indicate that late marginal eruptions accompanied subsidence of the maar.

The Strohner Maar is the result of a final flank eruption of the Röhmerberg volcano which earlier erupted mainly scoria. It is about 140 to 210 m. in diameter and threw fine-grained ejecta and large blocks to the north. Geomagnetic measurements indicate that the vent is inclined downward toward the south.

Maars in Iceland

(Noll 1967)

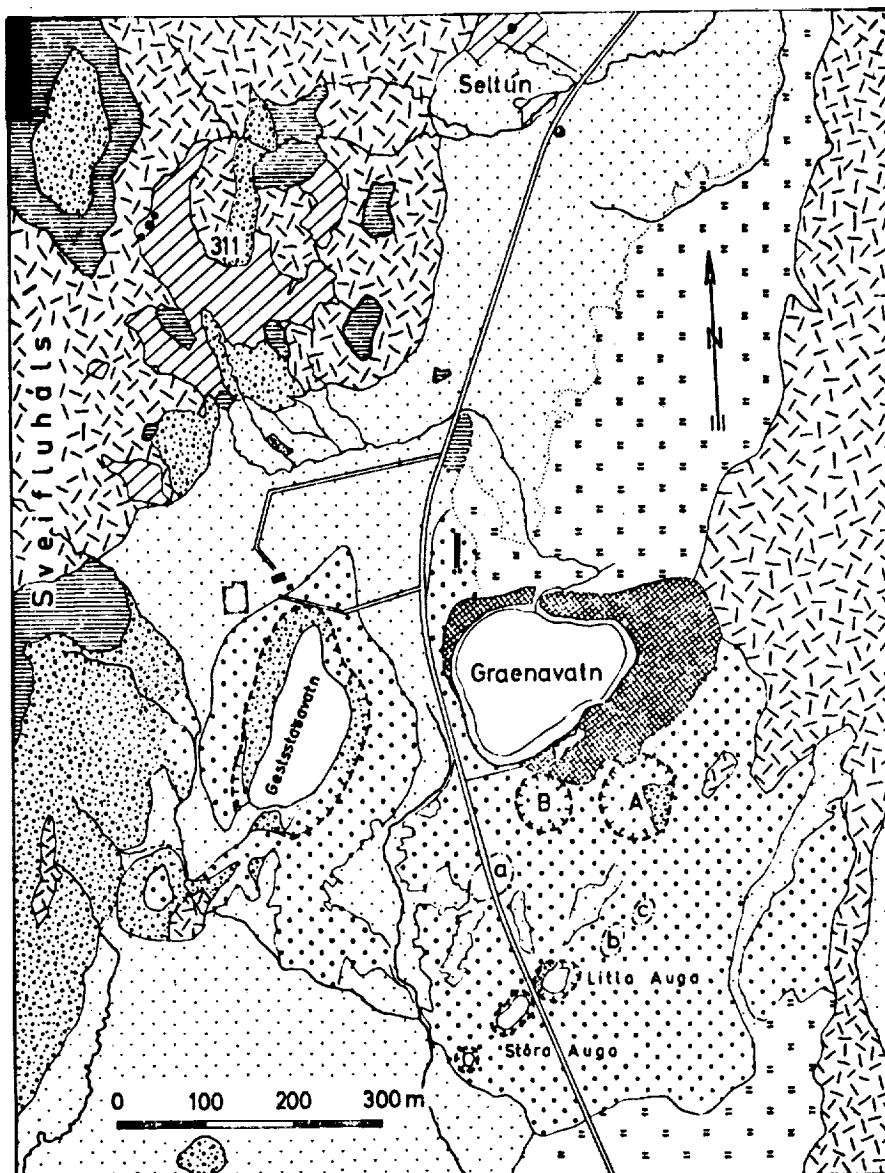
Volcanism in Iceland is mostly effusive and related to fissures. Craters with floors below the general ground level--maars--are quite rare and due to unusual conditions.

Graenavatn and Gestsstadvtn are two postglacial maars near Krisuvik on the Reykjanes peninsula in southwestern Iceland. They are located in a broad valley cut into the 'palagonite formation.' Postglacial fissure eruptions have been common and thermal activity is presently found at Krisuvik.

Graenavatn measures 340 by 260 m. and contains a lake with a maximum depth of 44.7 m. and eruption deposits up to 11 m. thick. The slope within the crater has a maximum angle of 52° ; the floor is flat and covered with sediments. The eruption first ejected coarse unbedded breccia containing accidental blocks up to 4 m. across and a small amount of juvenile cinders and lapilli. The volume of the breccia is about the same as that of the crater. Subsequent eruptions produced cinders, then agglutinated spatter, and then more cinders. Gabbroic inclusions are found in this sequence. Finally, violent gas or steam eruptions deposited large blocks of country rock on top of the cinders. Some of them measure 2.8 m. across.

The initial eruptions are believed to have been caused by phreatic explosions which triggered the rise and eruption of fresh magma. The final eruptions may also have been caused by groundwater throwing out slumped blocks from the crater wall.

Viti in northern Iceland is one of the few examples of a maar formed in recent time. Its eruption in 1724 coincided with the beginning



Geologische Karte von Krísuvík











- | | | | |
|---|--------------------------------------|---|---|
|  | Palagonitbrekzie |  | Wälle von Schlackenkratern |
|  | Basaltische Wurfslacken |  | Fragliche flache Hohlformen |
|  | Schweißslacken-Laven |  | Solfataren-Gebiete und Schlammstöpe |
|  | Sprengschutt von Grænavatn |  | Äolische Überdeckung u. verschwemmte Zersetzungs-Produkte d. Solfataren-Gebiete |
|  | Juvenile Auswurfmassen von Grænavatn |  | Anmooriges Gelände |

Figure 7. Geologic map of the area around Grænavatn, southwest Iceland.

From Noll, 1967.

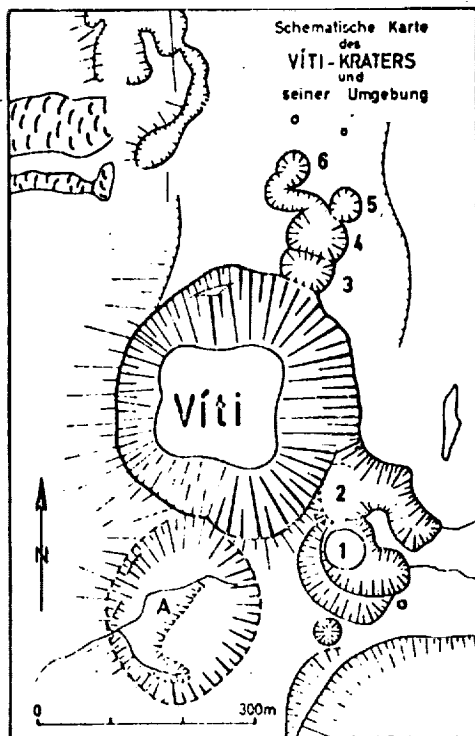


Figure 8. Sketchmap through Viti, the small craters 1 - 6, and an older crater A. From Noll, 1967.

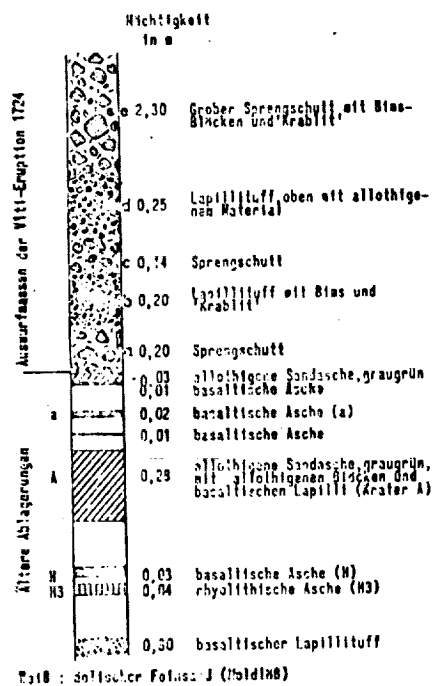


Figure 9. Section through north wall of Viti, Iceland. From Noll, 1967.

Maars in Iceland

of a fissure eruption which lasted from 1725 to 1729. The maar lies on the western slope of Krafla, a palagonite-breccia ridge, which is also known to have had postglacial fissure eruptions and thermal activity.

Increasingly strong earthquakes were felt the night before May 17, 1724, and at nine o'clock next morning a high ash cloud was seen. Flames and lightning are also said to have been observed. Increasingly strong earthquakes caused several houses 11 km. away to collapse. Vertical ground displacements took place east of Lake Myvatn, and the lake level temporarily subsided. East of the lake a meter of ash is said to have been deposited. The duration of the eruption is not given in contemporary descriptions.

The crater Viti is 320 m. in diameter, 53 to 102 m. deep and is occupied by a lake. Pyroclastic ejecta, most of which were thrown to the south-southeast, measure 12 m. thick at the southern rim. They consist of very poorly sorted coarse fragments of country rocks with two interlayers of well-sorted juvenile lapilli and cinders. Fragments of intrusive rhyolite are common. The largest blocks of country rock ejected measure 1.5 m. across. Six smaller craters were formed simultaneously in the surrounding area along a fissure. An older crater just south of Viti was formed near the end of the 14th. century.

The 1724 eruption started with gas rising along a fissure and the formation of small craters, but was soon concentrated at a point, forming Viti crater by strong eruptions of lithic debris. Intermittently, juvenile fragments were thrown out. The final strong gas eruption gave the crater its present shape; it threw out little more than country rock. The gases may have been partly of juvenile origin but the influence of groundwater cannot be questioned.

Maars in Iceland

In 1814, mud eruptions were observed in one of the small craters at the southeast margin of Viti. Thermal activity still continues.

Several other maars are known in other parts of the neovolcanic belt of Iceland. They vary in diameter from 100 to 530 m. and in depth from 5 to 70 m. Most were formed by initial gas eruptions preceding normal basaltic cinder and lava-producing eruptions. Their coarse debris consists of unsorted and unbedded lithic debris. In some cases, groundwater was almost exclusively responsible for the formation of the maars; in a few cases, maars were formed at the close of fissure eruptions, a typical example being Kerid in southwest Iceland.

Kerid lies at the northern end of a northeast-trending crater group, 1 km. long, from which cinders and lavas were erupted more than 6420 years ago. Activity moved from southwest to northeast. Glaciated lavas and fluvio-glacial deposits were covered by cinders and agglutinate that accumulated around the orifice. The rise of lava and formation of a lava lake is indicated by lava-aprons and vertical grooves in the crater wall. Subsequently, some lava escaped from the crater to cover an area of about 3.78 km^2 . A final eruption formed the present crater, 220 to 180 m. wide and 50 m. deep. The ejected debris consists of lithic material, completely devoid of any juvenile ejecta. The final eruption appears to have been essentially phreatic in origin, caused by contact of groundwater with magma.

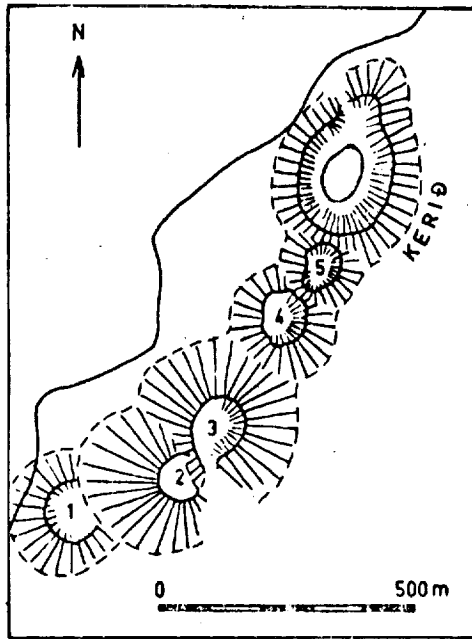


Figure 10. Sketch map of the cinder cones of the Tjarnarholar group, Iceland. From Noll, 1967.

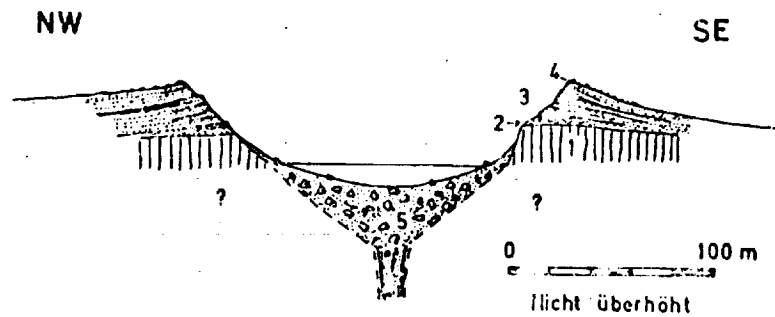


Figure 11. Section through Kerid, Iceland. 1) Basalt of the Lyngdalsheidi shield volcano; 2) fluvioglacial deposits; 3) cinders and spatter of cone No. 6; 4) thin layer of Kerid explosion debris; 5) explosion-debris in the funnel. From Noll, 1967.

The Pinacate Maars

(Jahns 1959)

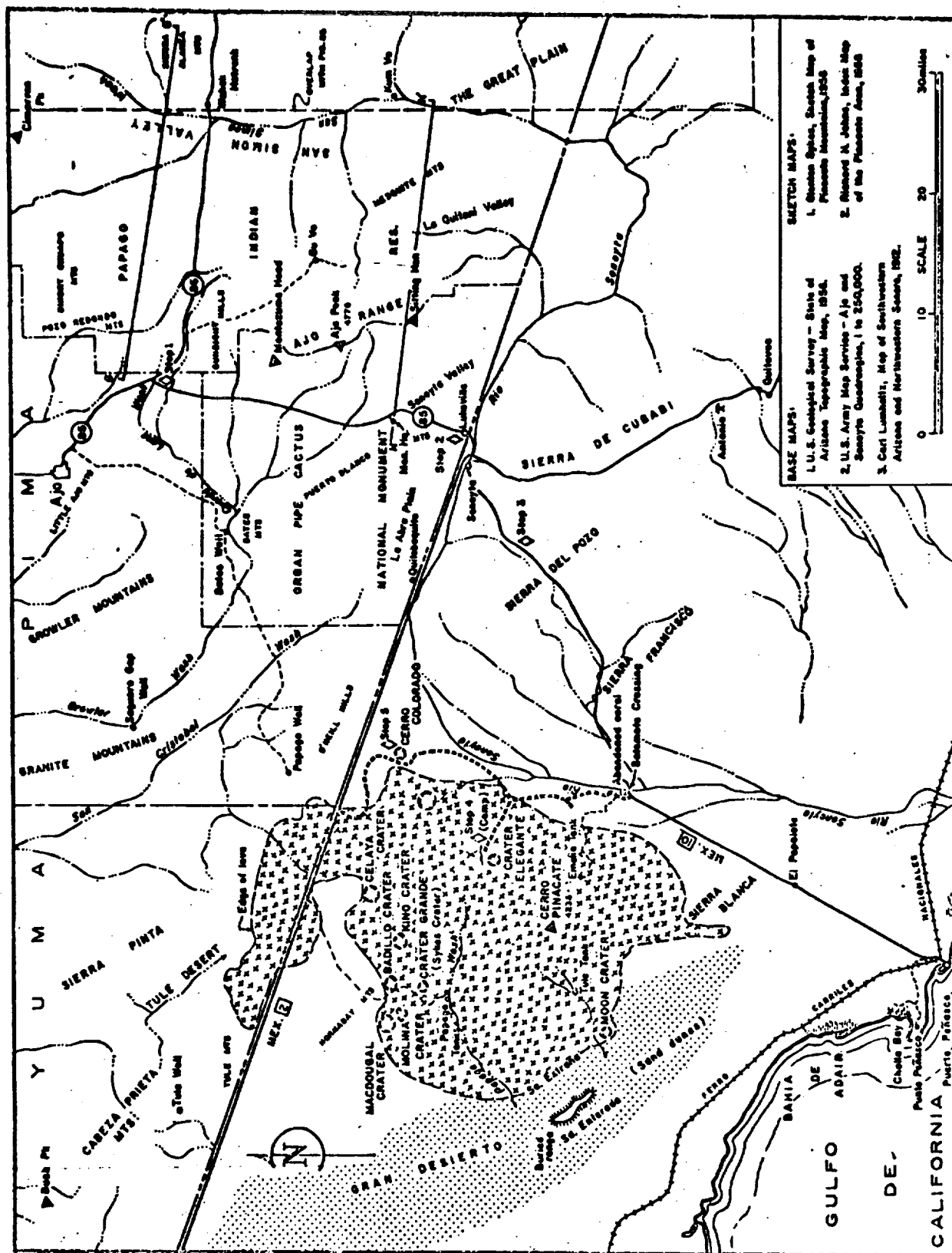
The volcanic rocks of the Pinacate region, northwest Sonora, Mexico, lie on a surface of considerable relief cut in pre-Tertiary plutonic and metamorphic rocks. They interfinger with Quaternary non-marine sediments, and extend in age from late Tertiary to Recent, the last eruption having taken place in 1935.

The volcanic rocks consist of fine-grained and locally porphyritic basalts containing plagioclase, hypersthene, olivine, and magnetite. They form flows, plugs, dikes, sills, cinder-cones and scoria-beds.

Eight maars are known in the region, seven of them lying on a west-to-northwest-trending arc, 30 km. long. They are circular to oval, with diameters from 750 to 1740 m. and depths from 36 to 245 m.; the diameter-to-depth ratio varies between 6:1 and 25:1. The outer slopes dip away gently from the craters, whereas the inner slopes are moderate to steep in their upper slopes, and marked below by precipitous walls and steep talus aprons that descend to flat floors. The wall-rocks consist of older lava flows and scoriaceous ejecta overlain by well-stratified pyroclastic materials ejected during formation of the maars. The pyroclastic rock deposits measure from 15 to 110 m. thick and consist of vitric ash, crystal-rich lapilli and small bombs. In addition, there are fragments, up to 6 m. across, derived from the Pinacate basalts and pre-Tertiary rocks. The grain-size of the deposits varies widely, but is mostly rather fine.

The pyroclastic beds normally dip away from the craters, but inward-dipping beds are also found, some of which can be traced to the

Figure 12 . Index map of southwestern Arizona and northwestern Sonora, Mexico, showing the location of the Pinacate Mountains. From Jahns, 1959. ^{80.}



The Pinacate Maars

youngest out-ward dipping pyroclastic beds. Graded bedding, slump marks, ripple marks, cross-bedding and impact sags are common features.

Very little material from the wall rocks is present among the pyroclastic beds; hence, the volume of the craters must be explained in terms of subsidence. The maars were formed principally by collapse of tephra rings and cones, the lower slopes of which form the rims of the depressions. Collapse is assumed to have been caused by withdrawal of magmatic support after violent eruptions.

Arcuate faults within Kino Crater and subsided rim-beds in the floor of Crater Elegante indicate subsidence along nearly vertical ring-faults. Subsidence still continues on a small scale in Crater Elegante and Cerro Colorado. Some maars experienced renewed activity, caving of the walls and formation of lake beds and playa deposits. The arcuate distribution of the seven northern maars coincides with the distribution of water-bearing Quaternary sediments of the Río Sonoyta, suggesting that groundwater was involved in the phreato-magmatic eruptions.

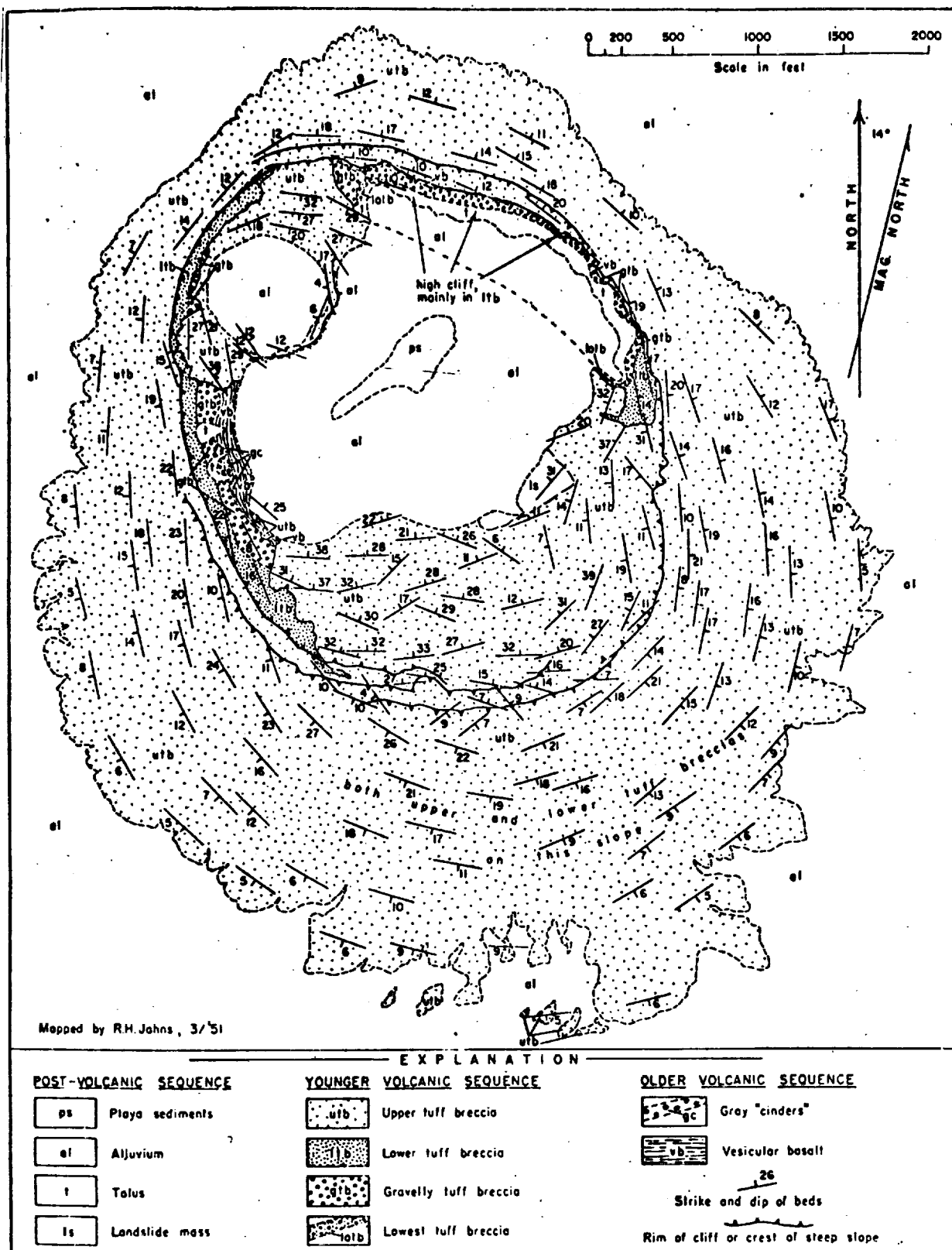


FIGURE 13. Geologic map of Cerro Colorado.

From Jahns, 1959.

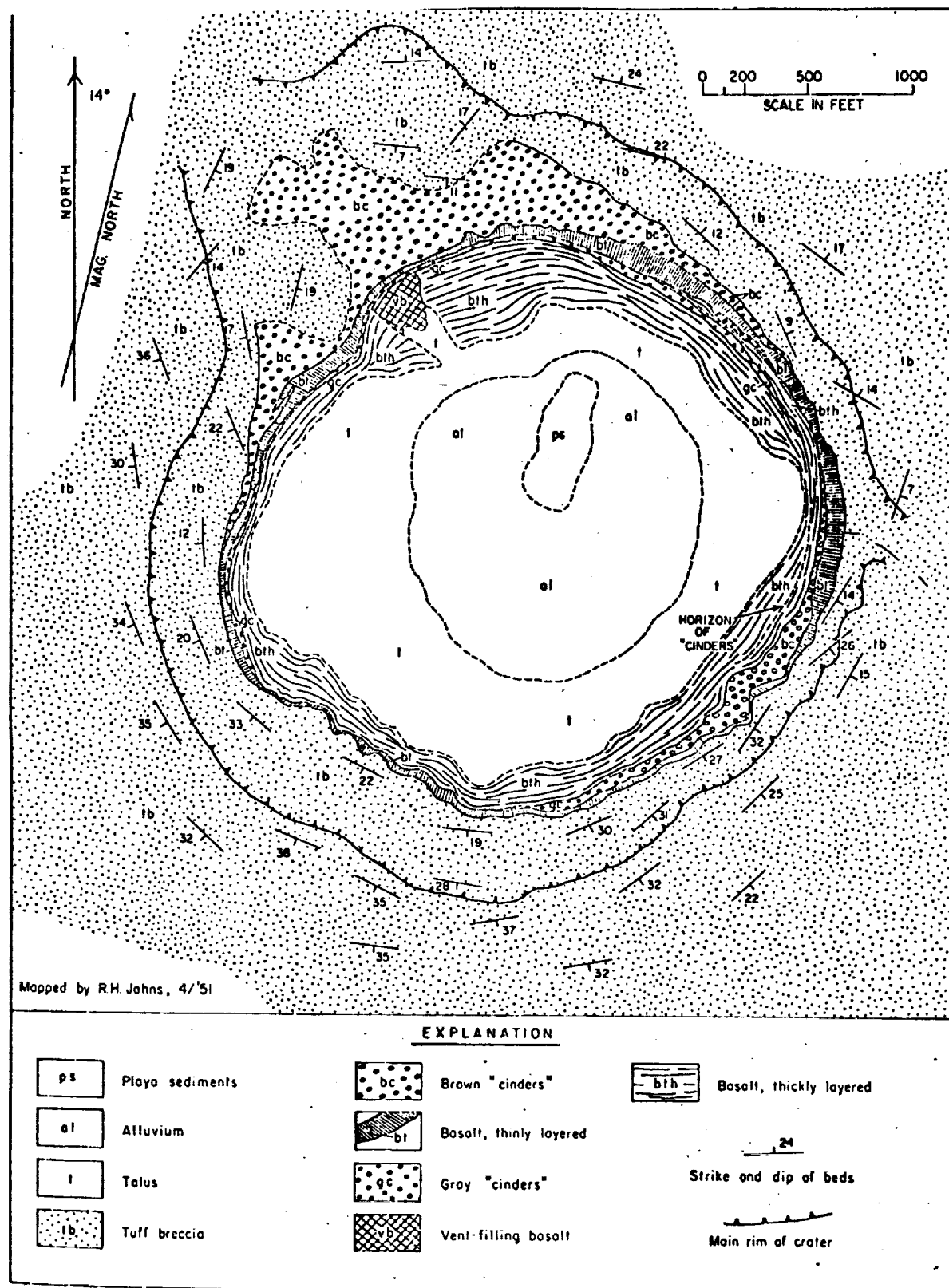


FIGURE 14. Geologic map of Crater Grande (Sykes Crater).
From Jahns, 1959.

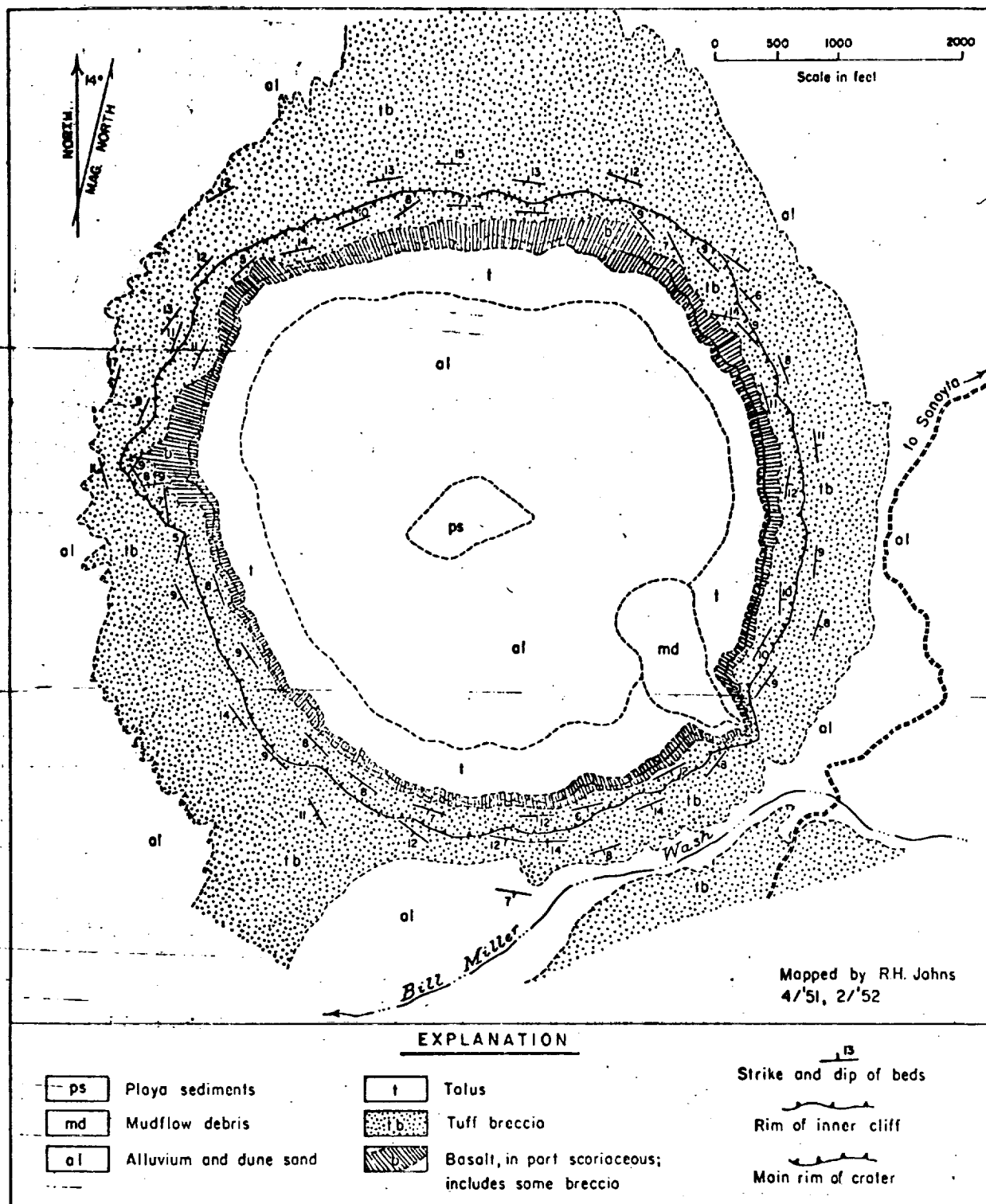


FIGURE 15. Geologic map of MacDougal Crater.

From Jahns, 1959

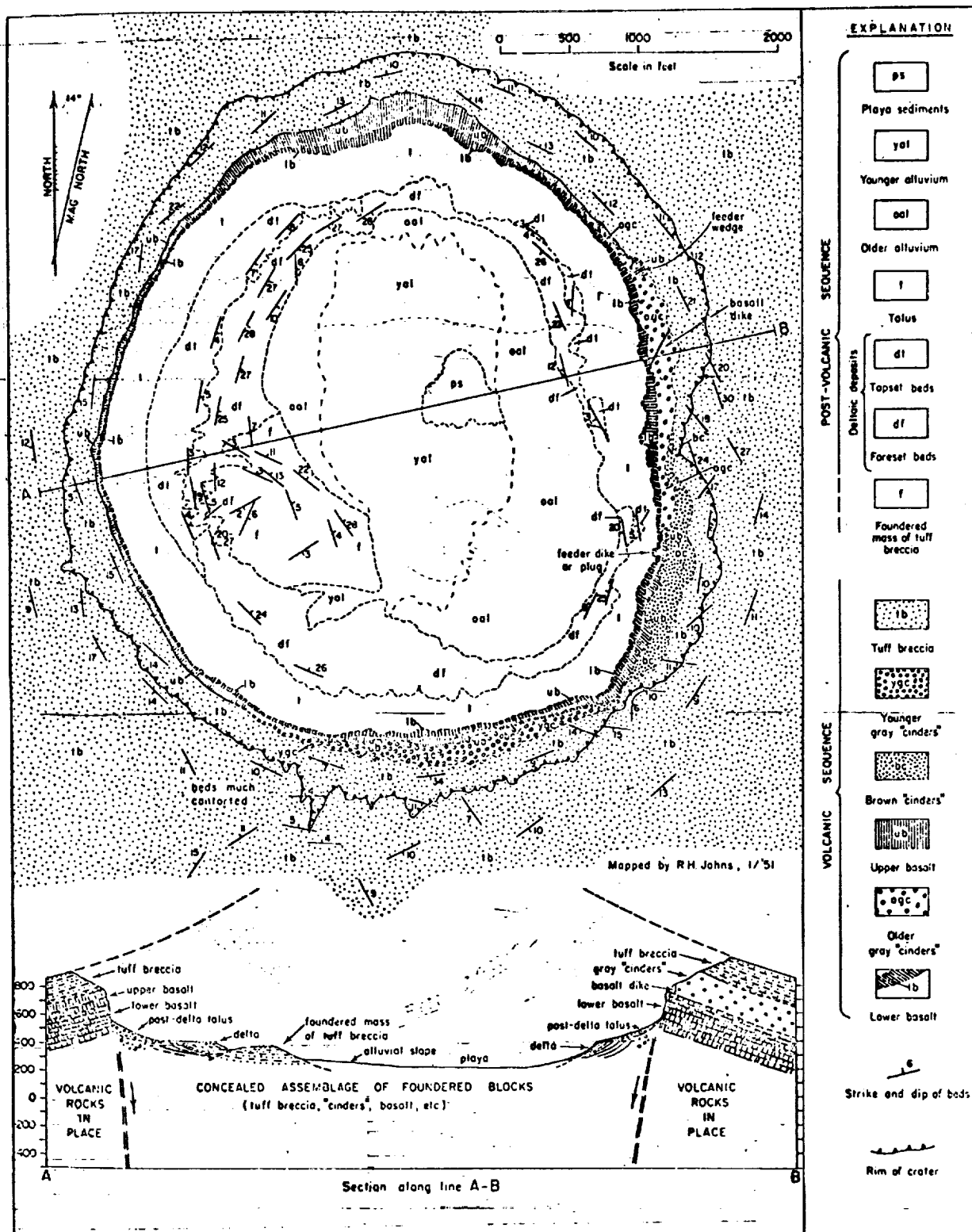


FIGURE 16. Geologic map and cross section of Crater Elegante.

From Jahns, 1959

Pretoria Salt Pan, South Africa
(Wagner, 1922)

Although most maars are found in volcanic regions, a few have no apparent relation to regional volcanism. An outstanding example is the Salt Pan crater near Pretoria, South Africa. This is a flat-bottomed basin about 130 m. deep, 1000 m. across, surrounded by a rim up to 70 m. high. It was formed by an explosion through ancient crystalline basement rocks, no volcanic fragments having been recognized among the ejecta. Although the crater was emplaced in the Precambrian Bushveld granite, the eruption threw out fragments of rocks not exposed in the vicinity, including norites similar to the principal rock-type of the Bushveld layered intrusion--soda syenite, foyaite porphyry and dolomite breccia containing chlorite schists and quartzites of uncertain origin.

Prior to the eruption, the Bushveld granite had been eroded to a moderately level surface and capped by Coal Measure Grits of Cretaceous Karroo beds. When the maar was formed, the Karroo rocks formed a thin veneer less than 10 m. thick, consisting of crudely bedded subangular and rounded quartz grains averaging about 3 mm. in size, set in a clayey matrix, along with a few interbeds of iron-rich lateritic clays. Large boulders of the underlying granite are present near the base of the Karroo beds; below the unconformity, the granite is strongly decomposed and kaolinized. Hence, rocks derived from this shallow, weathered horizon are readily distinguishable from the fresh angular blocks of granite derived from greater depths and now present among the ejecta.

The granite below the sedimentary horizon is increasingly shattered at greater depths, and shows evidence of compressional shear

Pretoria Salt Pan, South Africa

along joint surfaces. In several places around the inner slope of the crater, a steeply dipping fault separates fresh granite inside from decomposed granite outside.

Wagner believed the sequence of events responsible for the maar to be as follows: 1, Updoming of the granite; 2, Phreatic explosion; 3, Subsidence and slumping. Ejecta cover the uparched pre-eruption surface to depths of up to 40 m. Non-granitic fragments tend to occur in clusters and are most abundant in the upper layers, suggesting that the explosions proceeded downward from shallow levels.

The floor of the crater is covered with saline evaporite deposits and a small pond derived mainly from meteoric water. The water is rich in chlorides and bicarbonates of sodium, probably leached from the surrounding rocks. Holes drilled through the floor indicate that the saline deposits are underlain by a downward-tapering breccia pipe. The ejecta show little thermal alteration. No fragments of the magnetite layers in the upper part of the Bushveld norite are present; the depth of the explosions was therefore less than about 3000 m.

Wagner's conclusion was that the maar was formed by low temperature blasts of steam and CO_2 , which first domed the granite then broke through to the surface. Subsidence and slumping then widened and deepened the crater. The source of CO_2 may have been a carbonatite intrusion, such as those associated with small soda syenite bodies in the same region.

Rohleder (1933) and Baldwin (1963) suggest that the Pretoria Salt Pan may be a meteorite impact-crater. They cite the uplifted country rock of the rim, which is indeed very unusual for maars, the inverse

Pretoria Salt Pan, South Africa

stratigraphy in the ejecta, and evidence of shattering and compressional shear in the wall and ejecta.

Gour de Tazenat

Crystalline basement rocks also form a large proportion of the ejecta of the maar of Tazenat near the northern end of the Chain of Puys in the Auvergne region of Central France. The maar measures about 1.5 km. in diameter and is slightly larger than the Salt Pan just described. It is about 67 m. deep and contains a freshwater lake.

Volcanic debris forms only a small fraction of the crescent-shaped rim of ejecta around the northern side of the crater. The principal fragments in the ejecta consist of ancient granites and granulites of the basement series, but volcanic scoria increase in abundance upward. Many other vents lie along the same north-south trend of the chain, but these consist almost entirely of volcanic scoria, or are marked by viscous domes and subordinate lavas. Why the Gour de Tazenat differs so markedly from these other vents is not clear. Glangeaud (1913) suggested that the magma reservoirs under the chain was deeper toward the extremities of the fissure system. It is impossible to judge the depth of the explosion foci from the nature of the ejecta, but at the nearby crater of Beaunit, Brousse and Rudel (1964) found peridotites, gabbro, norite, charnockite, sillimanite-and-garnet-granulites and a variety of granitic rocks. These fragments represent the most complete sampling of the crystalline basement of central France, but the depths from which they were derived cannot be judged.

Tuff-rings on Oahu, Hawaii
(Wentworth, 1926; Hay, 1968)

More than 20 tephra-rings were formed along the south coast of Oahu during deposition of the Honolulu volcanic series in middle and late Pleistocene times. The tephra deposits consist mainly of fragments of sideromelane ranging in composition from undersaturated olivine basalt to melilite-nephelinite. Most of the sideromelane has since been converted to palagonite by low-temperature reaction with percolating groundwater. This alteration, as shown by Hay, was not one of hydration or devitrification but a microsolution-precipitation process, and the bulk-composition of the palagonite and included zeolites is not markedly different from that of the parent sideromelane.

The tephra-rings are approximately circular, with inner and outer slopes of 35° or less, and saucer- or bowl-shaped craters. Their diameters, measured at the rims, range from 400 to 2,200 meters. Diamond Head, for example, approximates 1 km. in diameter; Punchbowl, 600 m.; Koko Crater, 800 m.; and Salt Lake Crater measures 1.6 by 2.2 km. across. The rims of Salt Lake Crater nowhere rises more than 110 m. above the floor, which lies at sea-level; the rim of Diamond Head crater averages 125 m. in height, reaching a maximum of 232 m.; that of the Punchbowl reaches a maximum height of more than 145 m., and that of Koko Crater, which was strongly influenced by the wind-direction during the eruptions, ranges in height from about 150 to nearly 400 meters.

Bedding of tephra in the rims dips both inward and outward. Impact pits made by falling blocks are common; at Koko Crater, a few tephra beds reveal two sets of asymmetrical impact pits that indicate

(Tuff-rings on Oahu, Hawaii)

simultaneous eruptions from two craters, one northeast of the other. Blocks 1 m. across were sometimes blown 600 m. from the vents, which is equivalent to an initial velocity of at least 77 m./sec. and some blocks 10 cm. across were blown a distance of 1.6 km. which is equivalent to an initial velocity of 125 m./sec. In the walls of Salt Lake Crater, blocks of ultrabasic rock are concentrated at definite horizons within the finer ejecta. Most blocks are composed of basaltic lava, among which a few weigh several tons, and in some tephra-rings, e.g. Diamond Head, there are blocks of reef-limestone and 'beach-rock.' But the bulk of the tephra is made up of markedly vesicular juvenile ash, lapilli, and bombs up to 10 cm. across. Accretionary lapilli (pisolites), formed by condensation of water vapor around falling particles of ash, are plentiful in places, some of them measuring as much as 3 cm. in diameter.

All of the tephra-rings were built by short-lived phreatomagmatic eruptions. Indeed, Wentworth calculated that Diamond Head was built by discharge of 0.6 km.³ of ejecta within a few hours or days. Rising basaltic magma, coming into contact with abundant groundwater and sea-water, was drastically chilled to vesiculating sideromelane-glass and ejected in a rapid succession of explosions. Recent investigation of current-structures in the tuffs of Salt Lake Crater, near Honolulu, indicate that the ejecta were deposited not only by airfall but to a large extent by base surges (Fisher and Waters, 1970).

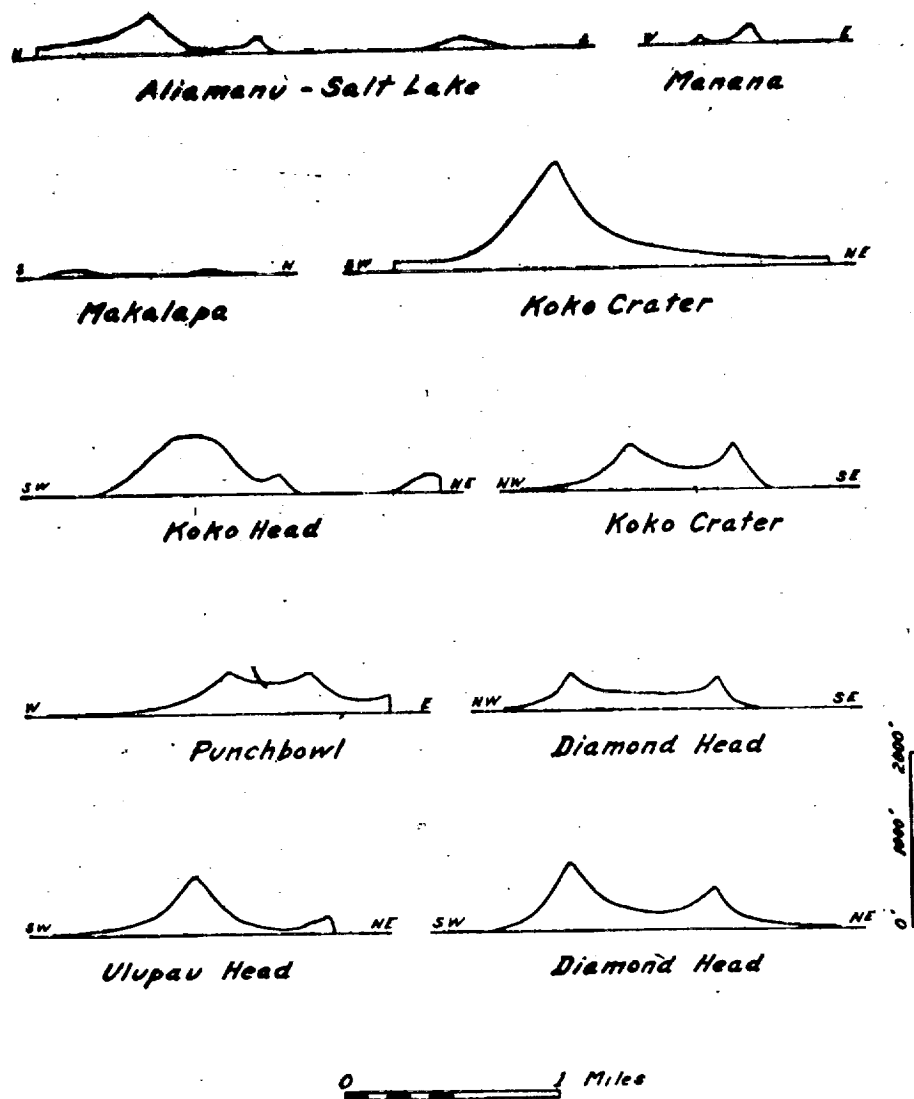


FIGURE 7.—Composite diagram showing the profiles of the principal tuff craters of Oahu. Vertical scale approximately twice the horizontal.

Figure 17. Composite diagram showing the profiles of the principal tuff rings of Oahu. Vertical scale approximately twice the horizontal. From Wentworth, 1920.

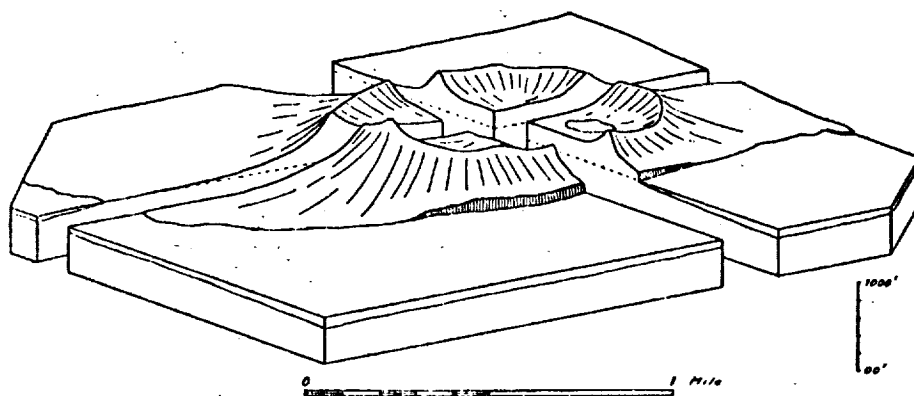


FIGURE 11.—Block diagram of Diamond Head dissected to show profiles in two directions.

Figure 18. Block diagram of Diamond Head, Oahu. From Wentworth, 1926.

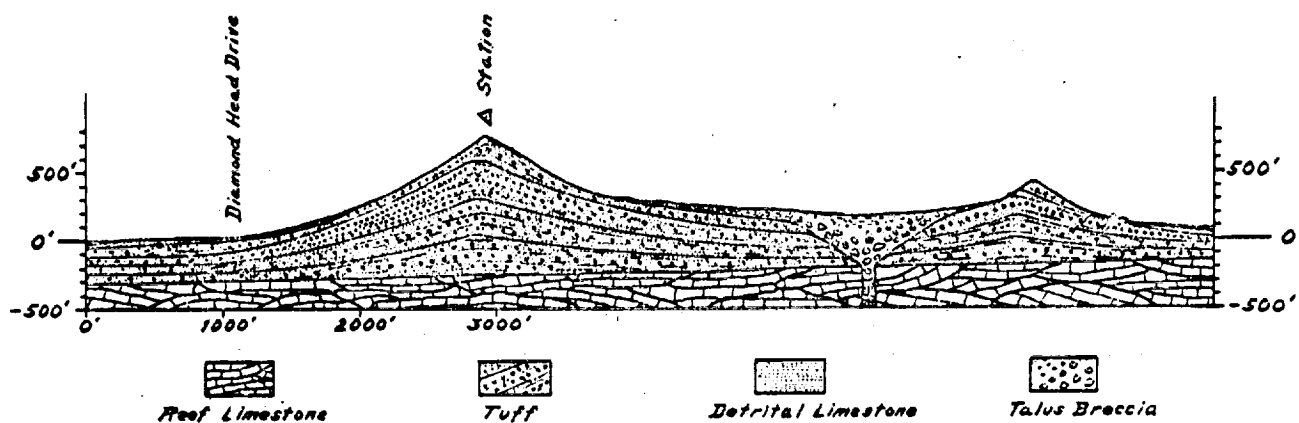


FIGURE 13.—Structure section of Diamond Head in a N.E.-S.W. direction through the summit peak. The structure of the reef limestone and of the filling of the vent is hypothetical. The structure of the main mass of tuff is interpreted on the basis of field observation of Diamond Head and other craters.

Figure 19. Section through Diamond Head. From Wentworth, 1926.

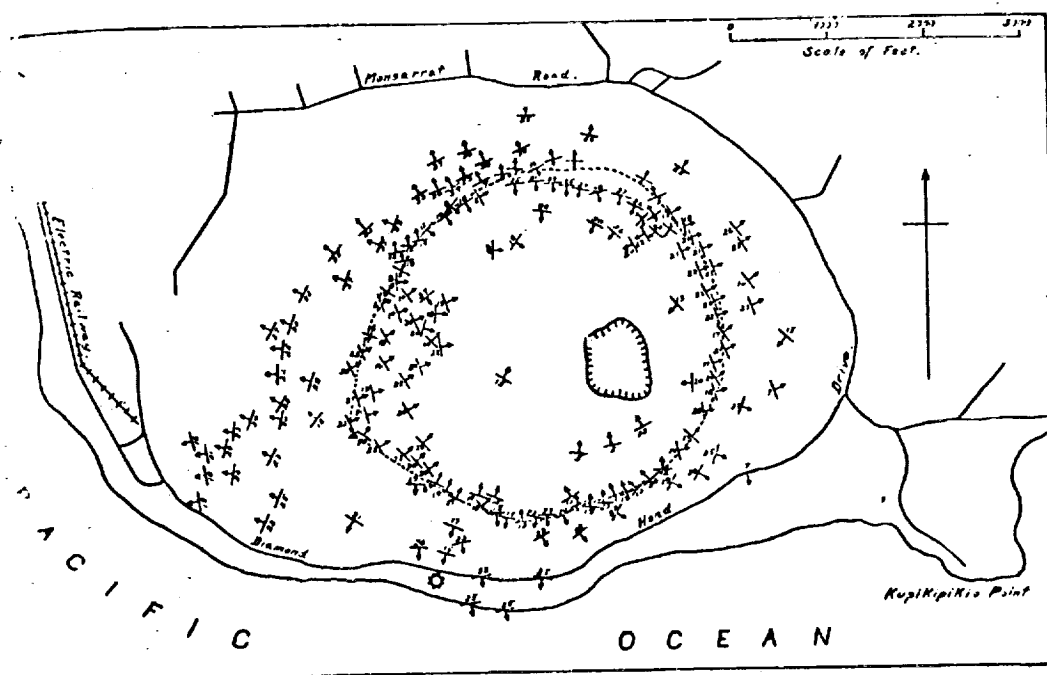


Figure 20. Structure map of Diamond Head showing the typical inner and outer radial dips. From Wentworth, 1920.

Tephra-rings in Iceland

(Thorarinsson, 1952 and 1960; Einarsson, 1965; Murray, 1967)

In the Myvatn area of northern Iceland, which is well known for its 'pseudocraters' and fissure eruptions, there are two magnificent examples of tephra-rings, namely Ludent and Hverfvall. Three cycles of volcanic activity can be distinguished in the area, each beginning with explosive discharge of tephra and continuing with discharge of lava from fissures. The first cycle started approximately 9,000 years ago with formation of the Ludent tephra-ring, and ended more than 6,000 years ago.

Ludent measures approximately 800 by 1,000 m. across. The crest of its crater-rim rises 35 to 115 m. above the flat floor, and this lies approximately 18 m. above the hilly area to the east of Ludent. The outer slopes of the tephra-ring dip at angles of 12° to 17° ; the inner slopes, at angles of 12° to 21° . In general, the pyroclastic beds dip outward at 7° to 36° , but on the southeastern wall. Some beds dip inward at angles of 40° to 47° . These beds, first detected by Lorenz in 1966, correspond to the youngest of the outward-dipping layers and unconformably overlies older beds.

The tephra deposits are well stratified and contain xenolithic blocks up to 2 m. across, some of which produced impact pits when they landed from flight. Most of the ejecta consist of vesicular particles of sideromelane, between 0.5 and 5 mm. in diameter, containing crystals of plagioclase, olivine, and augite. Mingled with these juvenile, magmatic ejecta are chips of lithic debris derived from underlying lavas. Small, smooth-walled vesicles are also to be seen within the tuff itself, in addition to those within the individual particles. They become more

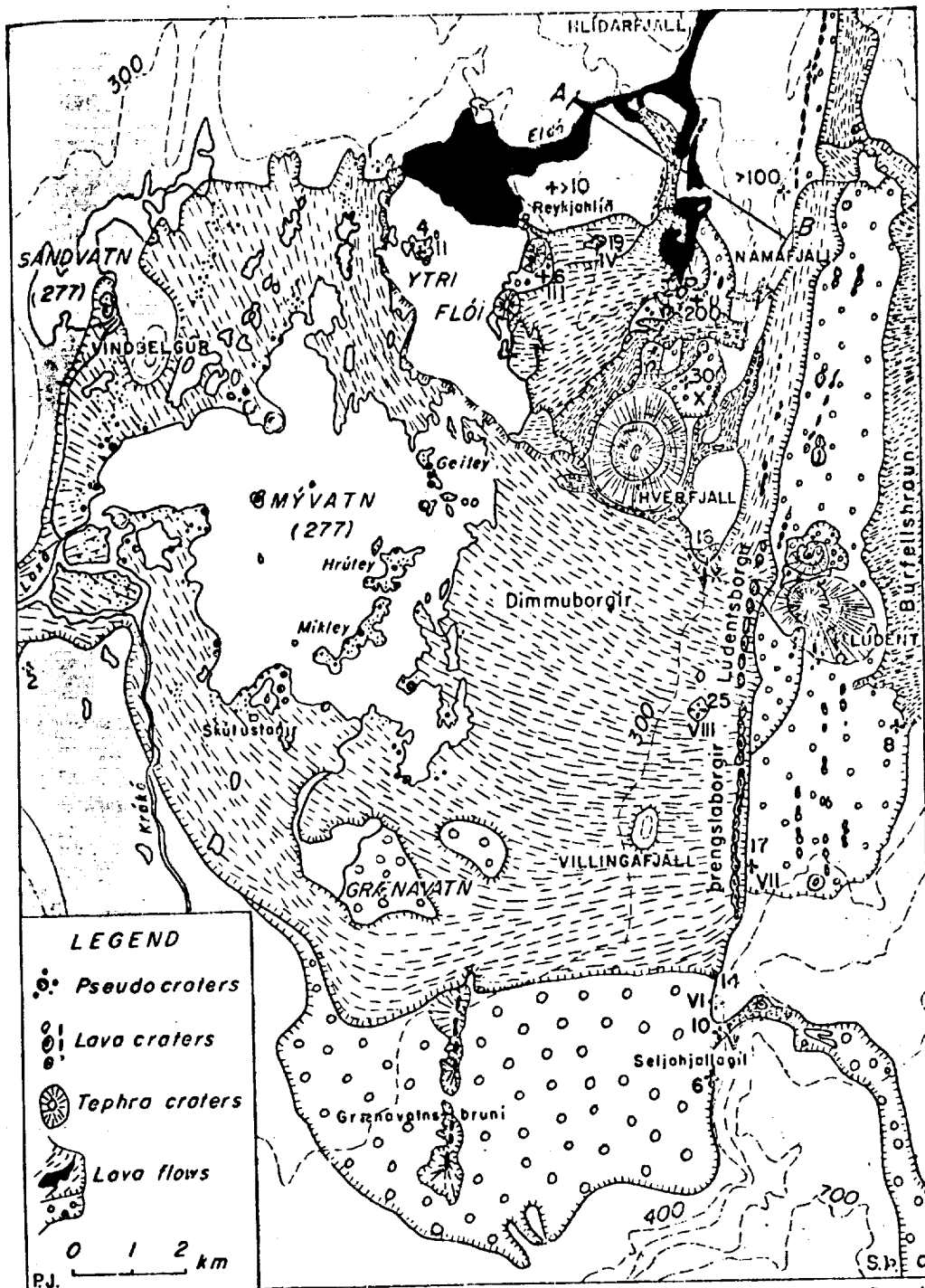


Fig. 13. Geological map of the Mývatn area. The bedrock (shaded) outside the postglacial lava flows is Pleistocene and covered by till and glaci-fluvial sediments. Small open rings: Lava flows of the Ludent cycle (>6000 years). Big open rings: The older Laxárhraun. Striated: Lava flows of the Hverfjall cycle (2500–1000 years). Black: Lava flows of 1724–1729. Roman numerals: Soil profiles on Fig. 12. Arabic numerals: Thickness of the Hverfjall tephra (h) in cm.

Figure 21. Geologic map of the Mývatn area showing location of Hverfjall and Ludent. From Thorarinsson et al, 1900.

(Tephra-rings in Iceland)

numerous upward in the section, but their mode of origin remains problematical.

After the Ludent tephra-ring had been built, its form was modified slightly by the development of several small craters, by eruptions of lava along and close to the rim, and by partial coating of the inner slope with lava and scoria. In addition, two viscous effusions of andesite formed the small dome of Hraunbunga on the northern rim.

The second volcanic cycle began about 2,500 years ago with formation of the Hverfjall tephra-ring, and continued with fissure eruptions from Threnslaborgir and Ludentsborgir until a few centuries ago. Hverfjall measures approximately 1.6 km. in basal diameter; its rim, which measures 1 km. across, rises about 150 m. above both the flat crater floor and the surrounding terrain. A mound that rises approximately 40 m. above the center of the crater floor is connected to the southwest rim by a low ridge. The outer slopes of the Hverfjall ring are inclined at angles of 17° to 30° , and the inner slopes at 17° to 35° , whereas the slopes of the central mound are inclined at angles of 17° to 27° .

The pyroclastic beds composing the ring generally dip outward 20° to 42° ; in the central mound, their outward dip increases from 14° near the base to 38° at higher levels. But in the lower parts of the inner slopes, on the eastern and southeastern sides, there are beds that dip inward, at 14° near the crater floor and at 41° higher up. These lie unconformably on the outward-dipping beds.

The tephra composing the Hverfjall ring consist chiefly of vesicular fragments of sideromelane, from 0.5 to 5 mm. in diameter,

containing crystals of plagioclase, olivine, and augite. Mingled with these magmatic ejecta are lithic fragments, a few of which reach up to 2 m. across. Some layers contain accretionary lapilli (pisolites). The total volume of ejecta is said to be approximately 0.5 km^3 , and of this amount, the lithic fragments make up only 2 per cent.

Most of the deposits are well-stratified, and, as in the Ludent ring, many lithic blocks lie within impact pits. And here, as there, the tuffs exhibit smooth-walled vesicles, from 1 to 5 mm. across, that increase in number upwards. The presence of these vesicles in the inward-dipping layers and in the tuffs of the central mound suggest that these deposits correspond to the youngest of the outward-dipping beds on the outer slopes.

After eruptive activity ceased, the crater was partly filled by a lake that left its highest strand-line 13.4 m. above the present floor.

The third and last volcanic cycle began on May 17, 1724, with eruptions that formed the Viti maar, already described in the section dealing with Icelandic maars. Following the explosive eruptions, effusive fissure eruptions continued for 4 years.

As to the origin of the tephra-rings of Hverfjall and Ludent, Einarsson concluded that both were formed under water, within a postglacial lake. However, the presence of abundant impact pits made by falling blocks militates against this view. Thorarinsson, with better reasons, favored the view that both rings were formed subaerially. Rising magma was suddenly chilled and fragmented when it came in contact with abundant groundwater, and so caused phreatomagmatic eruptions. The large diameters

(Tephra-rings in Iceland)

of the rings and the presence of inward-dipping beds lying unconformably on outward-dipping beds may imply that both the craters and vents were continually expanding as activity continued; alternatively, they may signify major collapses of the central parts of once higher tephra cones prior to deposition of the youngest inward- and outward-dipping layers and prior to growth of the central mound within the Hverfjall ring.

Murray thought that the central cone and inward-dipping tuffs within the crater of Hverfjall represent the collapsed top of a former cone that rose far above the present rim; in our opinion, however, the evidence he presents is unsatisfactory.

Menan Buttes, Idaho

(Stearns, 1926; Hamilton, 1962)

Two well-preserved tephra-cones of olivine basalt were formed 30 km. north of Idaho Falls, Idaho, by eruptions through the watersoaked floodplain of the Snake River and underlying Quaternary basalts. They diverted the Henry Fork of Snake River from its original course, forcing it to swing around their eastern and southern slopes.

Winds were blowing northeastward during the eruptive activity; hence, the tephra-cones are asymmetrical, measuring 3.2 km. in length and 2 km. in width. Their craters vary from 60 to 120 m. in depth, and whereas the rim of the northern ring rises to a maximum height of 245 m. above the surrounding terrain, that of the southern ring rises to a maximum height of only 160 m.

At the rim-crest, the pyroclastic deposits exhibit mantle-bedding that dips both inward and outward at angles of approximately 35° . They consist mainly of sand- and gravel-sized, angular to round, microvesicular particles of sideromelane coated with palagonite. Mingled with these magmatic ejecta are abundant sand grains, pebbles, and cobbles derived by eruptions through the Snake River floodplain, together with blocks of older basalt up to 1.5 m. across. All told, this lithic debris constitutes approximately 1 to 2 per cent of the total ejecta.

The eruptions resulted from the repeated rise of basaltic magma along a fissure-zone traversing beds heavily charged with groundwater. In addition to the two main tephra-cones are three older rings and several tephra-ridges that appear to lie on the same fissure-zone. Rains accompanying the phreatomagmatic blasts probably account for the exceptional abundance of accretionary lapilli (pisolites), some of which measure 3 or 4 cm. in diameter, forming beds up to 2 m. thick.

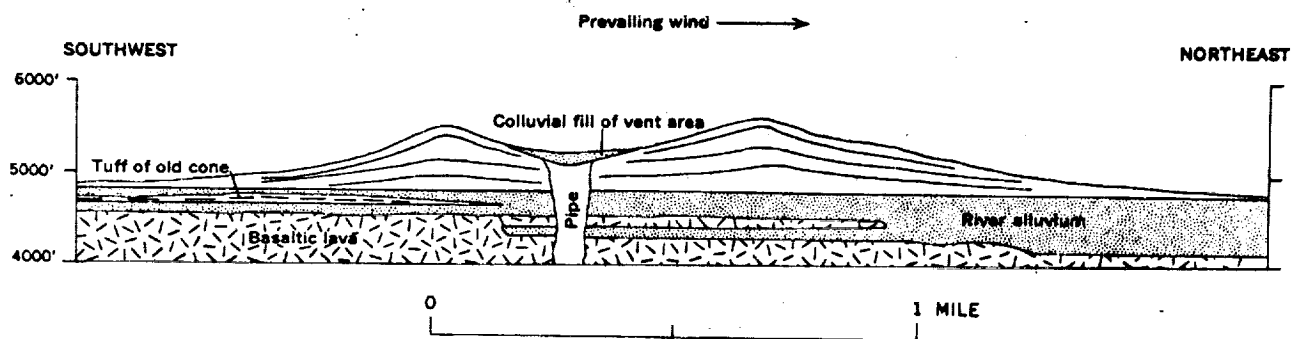


Figure 22. Section through North Menan Butte. From Hamilton, 1962.

Diatremes of the Schwabian Alb, South Germany

(Branco, 1894; Cloos, 1941; von Engelhardt and Weisskirchner, 1961; Papenfuss, 1963; Weisskirchner, 1967; Müssnest, 1969)

Branco, in his classic work on the Schwabian diatremes (Vulkan-embryonen), recognized 125 of them; since then, 210 more have been recognized, many by geomagnetic surveys. This impressive cluster of pipes, distributed over an area of approximately $1,600 \text{ km}^2$, was formed during Miocene times, beginning 20.4 m.y. ago and continuing for 5 to 6 m.y. At the present erosion-surface, they are surrounded mainly by Jurassic limestones and marls. Many of them form depressions on the limestone plateau or can be recognized by the occurrence of springs.

Formation of the diatremes seems to have been related to the rise of alkali olivine basalt magma that became ultramafic by contamination with carbonate-rocks, and its rise may have been related to orogenic movements in the Alps to the south. In any event, magma rose to the base of the sedimentary cover above the crystalline basement in the Urach area of the Schwabian Alb, where several graben, such as the Filder, Lauchert, and Fils graben, come together. At this level, the magma spread sideways to fill a large sheetlike chamber. Stratigraphic measurements suggest that the cover of Permian, Triassic, Jurassic, and Tertiary sediments is between 1,800 and 2,000 m. thick. However, geothermal investigations, taking cognizance of the present gradient of 11 to 18 m./°C., suggest that the cover is about 1,600 m. thick, while geomagnetic measurements suggest a thickness of 3 to 4 km.

Differentiation of the original magma was influenced considerably by reactions with carbonate rocks, and these reactions account in large part for the abundance of CO_2 among the erupting gases. Volcanism began

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with relatively high gas-pressures; accordingly, the first pyroclastic ejecta contain biotite and hornblende, as in the Bärzlen pipe. As activity continued, biotite and hornblende diminished in amount while olivine and pyroxene increased. Lime-rich melilite basalts, free from biotite and hornblende, were intruded into pipes and dikes at a late stage.

Development of the large sheetlike magma chamber caused slight doming of the sedimentary cover, and opened tension cracks trending northwest and northeast. The resultant release of pressure on the magma led to rapid exsolution of gas. Some cracks were filled by effervescing droplets of magma and shattered fragments of wall-rocks, forming pyroclastic dikes; other cracks were partly or wholly filled with melilite basalt. Most dikes range from 0.2 to 0.7 m. in width. The fillings of the pyroclastic ones show a rather uniform grain-size distribution with a maximum at 2 to 3 mm.

Cloos recognized 20 dikes in the region, but calculated on theoretical grounds that there might be 350 with a mesh-width of approximately 140 m. Papenfuss said that "magma dikes" have been seen in only 23 pipes.

Pipes formed preferentially at the intersections of tension cracks, and the major axes of elongate pipes trend northwest-southeast. Exposures are to be found on the summit of the Alb and on and in front of the escarpment. Consequently, the pipes can be examined at widely different erosion-levels. Most of them are approximately circular or irregular in outline. They measure from several hundred meters to more than 1 km. in maximum dimension, and they extend downward with steeply

inclined and nearly vertical walls. In detail, their margins are very irregular, following pre-existing joints and fissures, so that they show zigzag patterns and bayonet-like projections. Where vent-walls are composed of soft strata, they show intricate, serrated boundaries that belie an origin by violent explosive perforation; where they are composed of limestone, they commonly show scoring due to frictional drag.

The fillings of the pipes consist of a mixture of small basaltic lapilli and fragments of country-rocks that vary greatly in size. A few pipes also contain dikes and plugs of basalt. Most of the juvenile lapilli measure only a few millimeters across, though some range from 5 to 10 cm. across. Their typical shapes are spherical and ovoid, and usually each lapillus has an olivine or melilite crystal or a lithic fragment as a core enclosed by a shell of basaltic glass in which laths of melilite are arranged in a roughly concentric fashion. Large lithic blocks are generally angular and have subsided in the pipes from their original positions; most small lithic fragments, on the other hand, tend to be subangular or rounded and were carried upward from their source. Beautifully rounded and polished fragments of crystalline basement-rocks, once thought to have acquired their shapes by abrasion during long, upward transport, are now believed to have been derived from Permian conglomerates.

Cloos distinguished the following types of pyroclastic materials within the pipes.

1. Deposits, either bedded or unbedded, in the upper parts of pipes. Well-bedded deposits were laid down slowly and reworked in crater lakes (maars); the underlying, unbedded deposits accumulated by rapid back-fall of ejecta into maars.

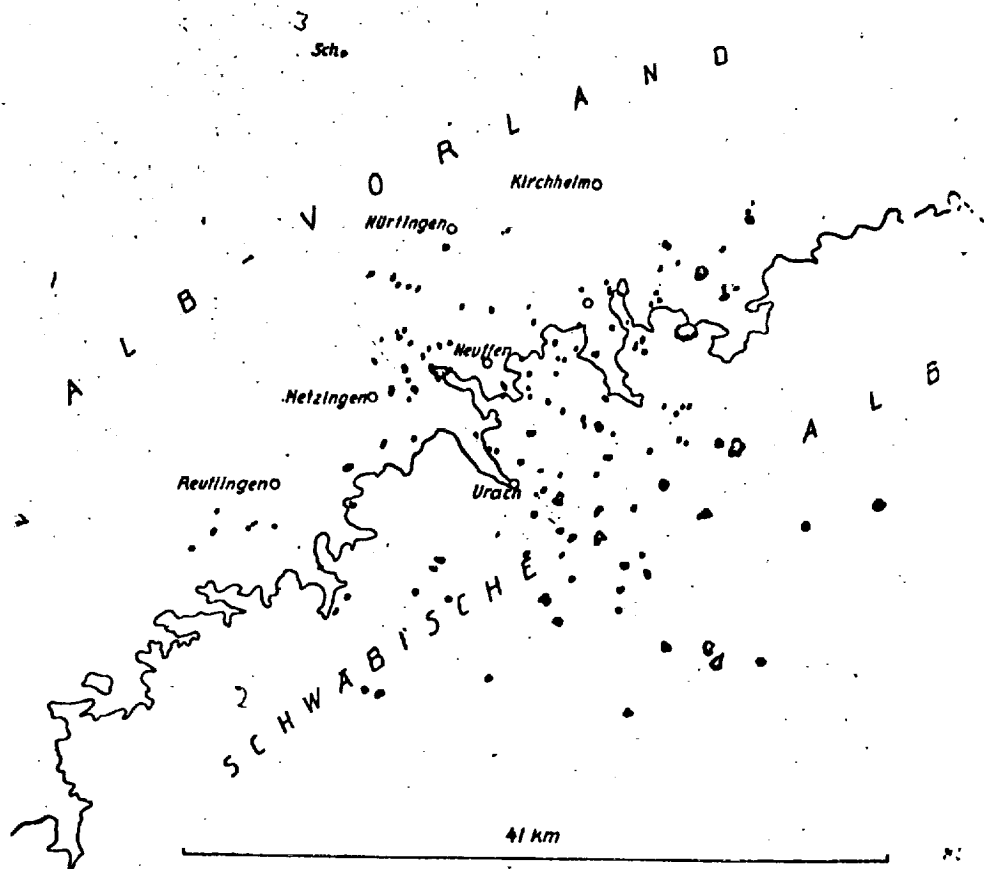


Figure 23 . Location of the Schwabian tuff-vents in relation to the edge of the Schwabian Alb. From Cloos , 1941.

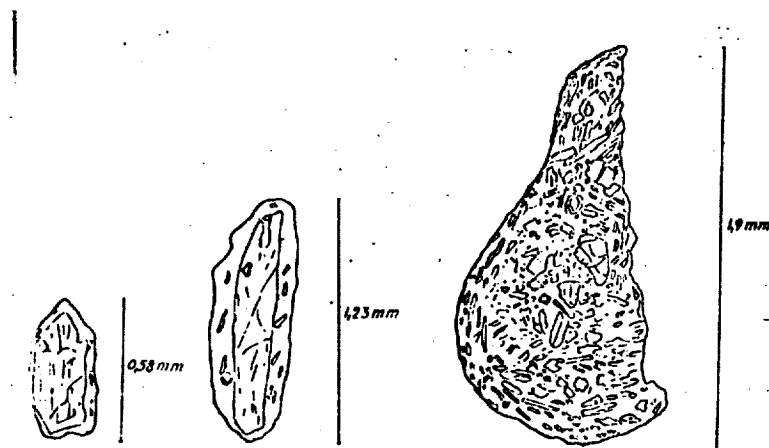


Figure 24 . Three basalt lapilli in thin section. Cores of olivine or melilite crystals surrounded by glass containing melilite laths some of which are aligned parallel to the surface. From Cloos, 1941.

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2. "Chain-stratified" deposits; i.e. flow-oriented pyroclastic ejecta aligned parallel to the walls of pipes or tangential to large blocks.

3. Unstratified, 'systematized' deposits, well-mixed and well-ordered in respect of size and spacing of the fragments, and also showing a regular grain-size distribution.

4. Unstratified, 'unsystematized' deposits devoid of order and showing no regular grain-size distribution.

Among the foregoing types, No. 3 represents the mature stage in the development of pipe-fillings.

There can be no doubt that most, if not all of the diatremes originally broke through to the surface, producing maars. The presence of fossiliferous, freshwater Tertiary sediments above some pipes confirms this view. The maars were formed partly by the eruption of ejecta and partly by intermittent subsidence of the diatreme-fillings during volcanism. Reworking of ejecta by water resulted in the formation of well-bedded deposits within the maars.

Bedding of the pyroclastic ejecta dips inward and as shown in diatremes on the erosion-scarp of the Alb, it becomes increasingly obscure downward. Beneath the lowermost bedded deposits, large subsided blocks of country rocks are surrounded and penetrated by pyroclastic debris along fractures, joints, and bedding planes. And the surfaces of limestone blocks in some pipes, particularly the corners and edges, are scored in various directions. This was caused by intense frictional stresses during intrusion of pyroclastic debris and by the abrasive action of uprushing ash-charged gas.

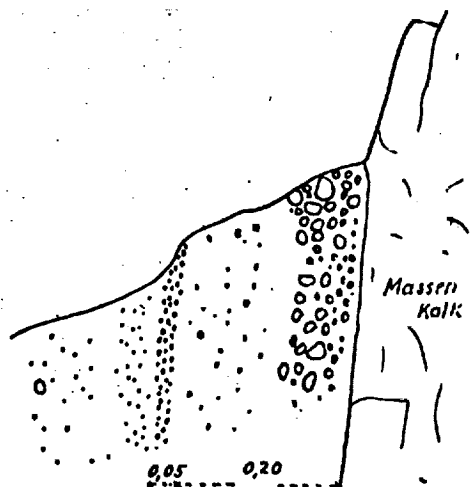


Figure 25. Flow-banding in otherwise unstratified tuff parallel to the boundary of a large block of massive limestone. The Jusi diatrema. From Cloos, 1941.

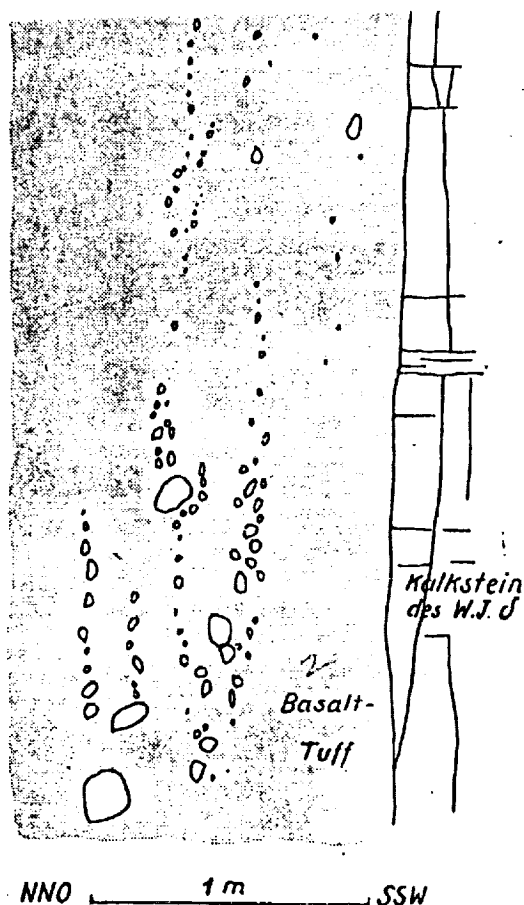


Figure 26. Southwest contact of the Neuffener Steige vent with flat-lying oolitic limestone. The tuff shows "chain stratification" parallel to the contact. From Cloos, 1941.

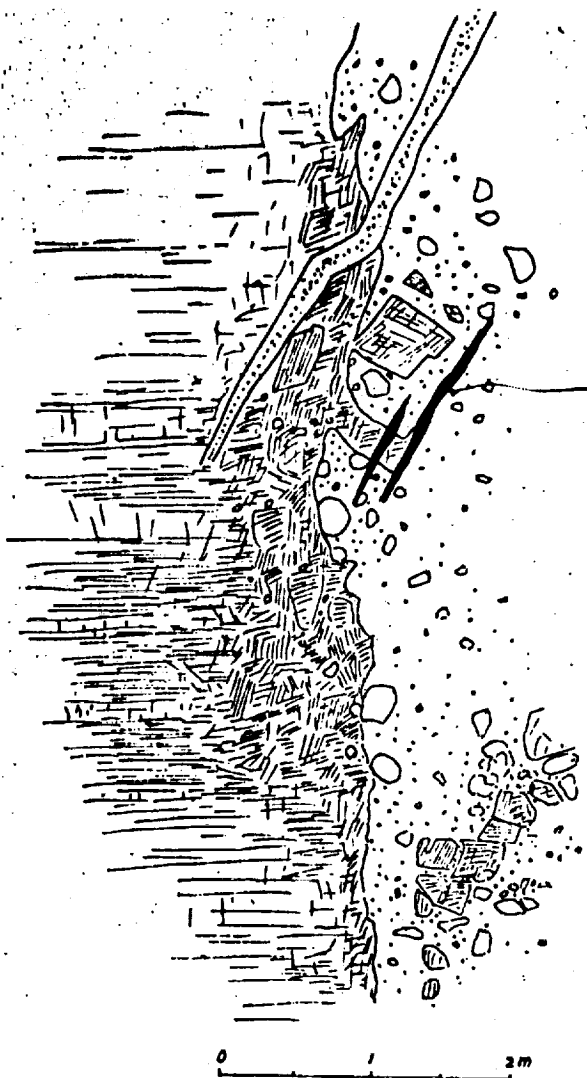


Figure 27. Serrated boundary between tuff (right) and Jurassic limestone at the outer contact of the Jusi vent, intersected by three dikes of finegrained tuff. From Cloos, 1941.

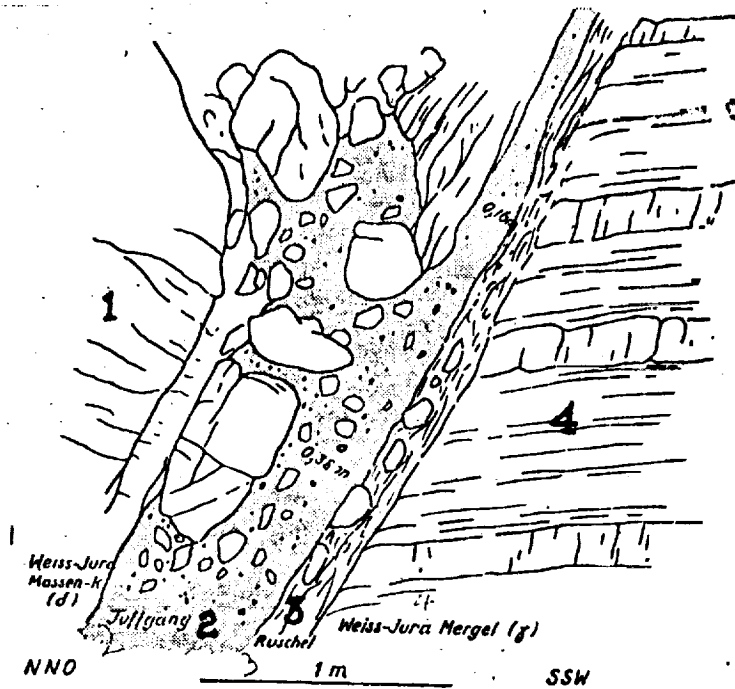


Figure 28. Tuff dike along a fault in limestone, northwest part of Jusi vent. 1) Jurassic limestone; 2) tuff dike; 3) fault-gauge; 4) Jurassic marl. From Cloos, 1941.

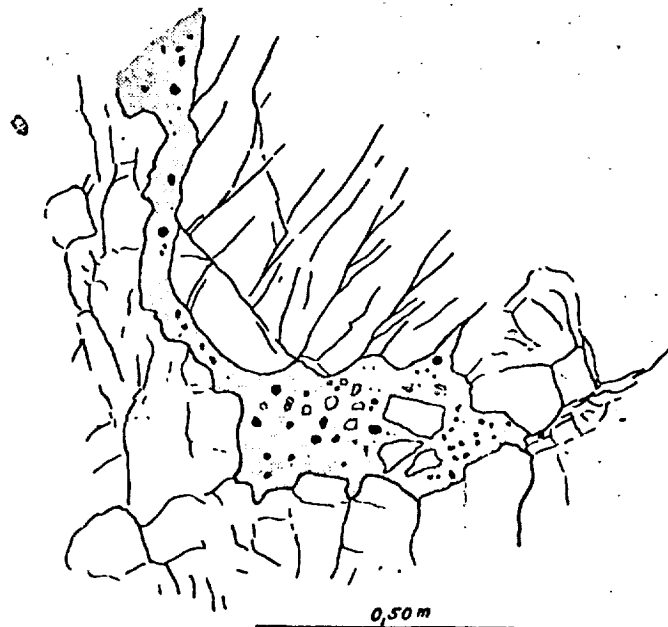


Figure 29. Tuff intruding block of massive limestone in the Jusi diatrema. Vertical section. Lapilli, shown as black spots. From Cloos, 1941.

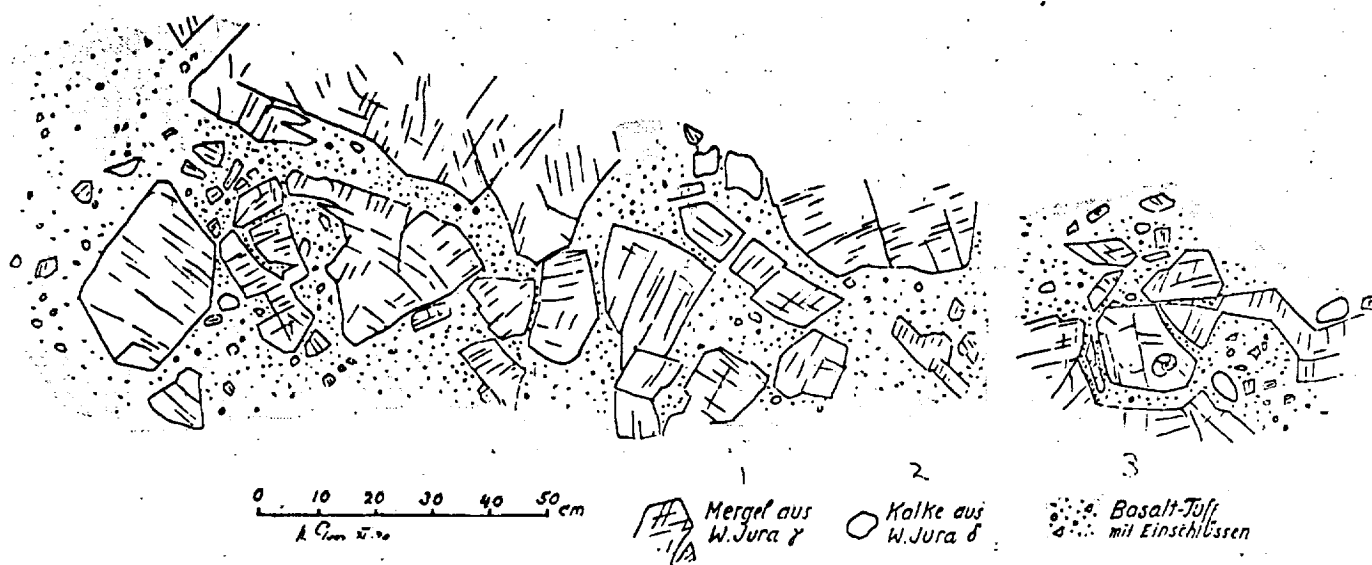


Figure 30. Basalt tuff in shattered Jurassic marl in the Jusi diatrema. From Cloos, 1941.

Cloos visualized the progress of activity to be as follows.

During the initial stage of feeble activity, fine-grained pyroclastic debris was discharged from open fissures. Papenfuss, however, considers these fine-grained materials to have been produced by an elutriation process within the pipes, and to have become incorporated in deeper, unstratified pyroclastic deposits. In any event, it was until after the initial feeble eruptions that activity became concentrated in localized areas, and not until then did activity become violent. During the main phase, rising gas, laden with particles, penetrated the country rocks along joints and cracks. Large blocks were detached from the walls and subsided slowly within the gas-particle system while small fragments were carried upward. Continued injection of pyroclastic debris into the blocks reduced their size by mechanical disruption, leading finally to their complete incorporation in the gas-particle system, and thus forming well-mixed and well-ordered deposits from the original unsystematized deposits. In some pipes, only a small amount of pyroclastic debris intruded the 'explosively brecciated materials, so that the stratigraphic sequence was preserved.

Late-stage subsidence of the entire fillings took place in some pipes so that the bedded pyroclastic deposits acquired steep dips near the margins. At the Randeck maar, subsidence continued even into Pliocene time. Late-stage hydrothermal activity led to cementation of the pyroclastic deposits and formation of carbonate dikes and veinlets. The maar measures about 1 km. wide at the rim, and between 60 and 80 m. in depth. A deep gorge cut through one side of the maar exposes deep levels of the underlying pipe. Bedded pyroclastic deposits on the floor of the maar

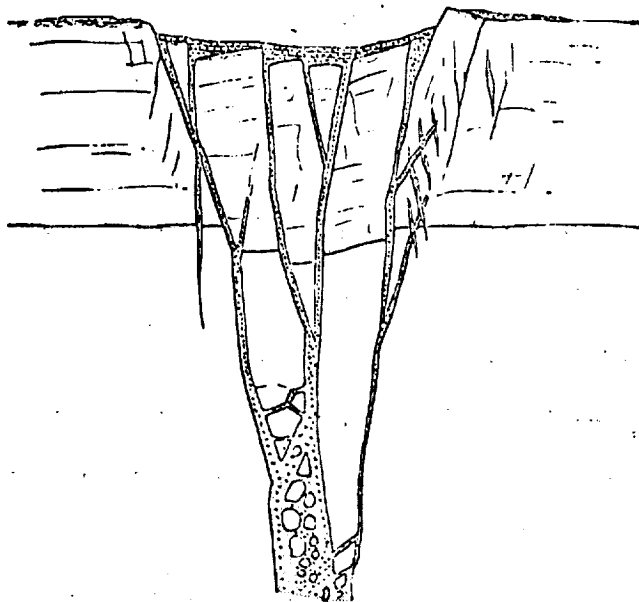


Figure 31. Early stage in the development of a Schwabian tuff-vent.

From Cloos, 1941.

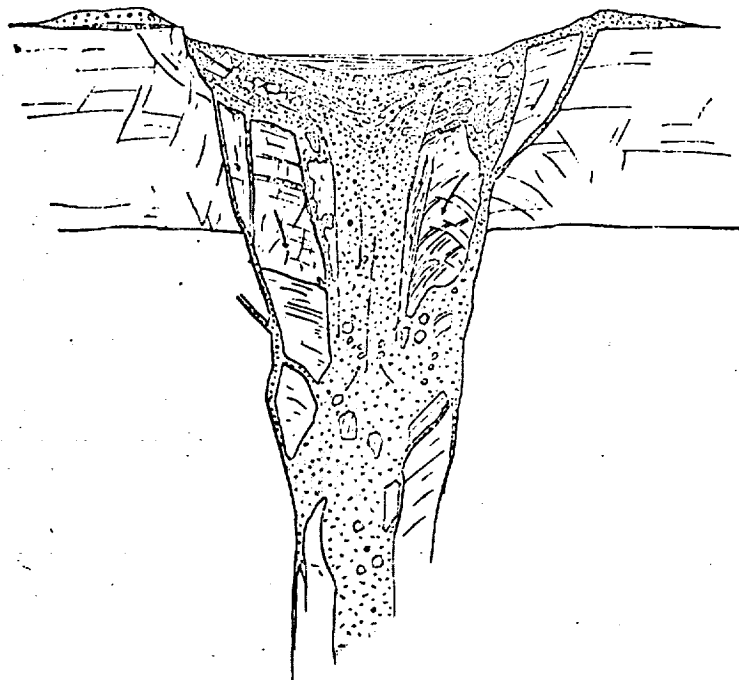


Figure 32. Final stage in the development of a Schwabian tuff-vent, based on observations of the Aichelberg, Jusi, and other diatremes. Basalt tuff containing small Jurassic blocks; also large blocks detached from the undisturbed walls. From Cloos, 1941.

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contain slumped blocks of wall-rocks; other blocks, penetrated by pyroclastic debris, are present at depths of 30 to 50 m. beneath the floor of the maar. At a late stage in the evolution of the maar, the deeper parts of the feeding pipe were intruded by tongues of melilite basalt. The occurrence of freshwater sediments of Late Tertiary age above the bedded pyroclastic deposits within the maar testifies to long-continued subsidence of the filling.

The Jusi pipe, one of the best studied, clearly demonstrates the various kinds of pyroclastic materials and their relationships (Cloos). Bedded pyroclastic deposits at the exposed top of the pipe indicate a crater-bowl about 1000 m. wide, at a depth of 130 m. below the original surface. Some of the deposits appear to have been laid down in water, and some contain blocks of country rocks that seem to have caved-in from the walls of the shallow maar. Close to the margins of the pipe, the deposits dip inward quite steeply and are cut by small-scale antithetic faults that indicate late-stage subsidence of the filling. Farther down the pipe, stratification due to fall-back of the ejecta into the vent becomes less distinct and finally disappears. Large blocks within the near-surface bedded deposits slumped from the walls. At greater depth in the pipe, below the bedded deposits, there are large blocks of country rocks, up to several hundred meters across, that lie 200 m. or so below their original positions. Most of them are riddled with stringers of pyroclastic debris, indicating stages in progressive disruption. Zones of well-mixed and well-ordered pyroclastic debris mark more mature stages of disruption.

The Eichelberg pipe contains an unusually large block of Jurassic limestone that dips inward at a high angle. If the block were rotated back

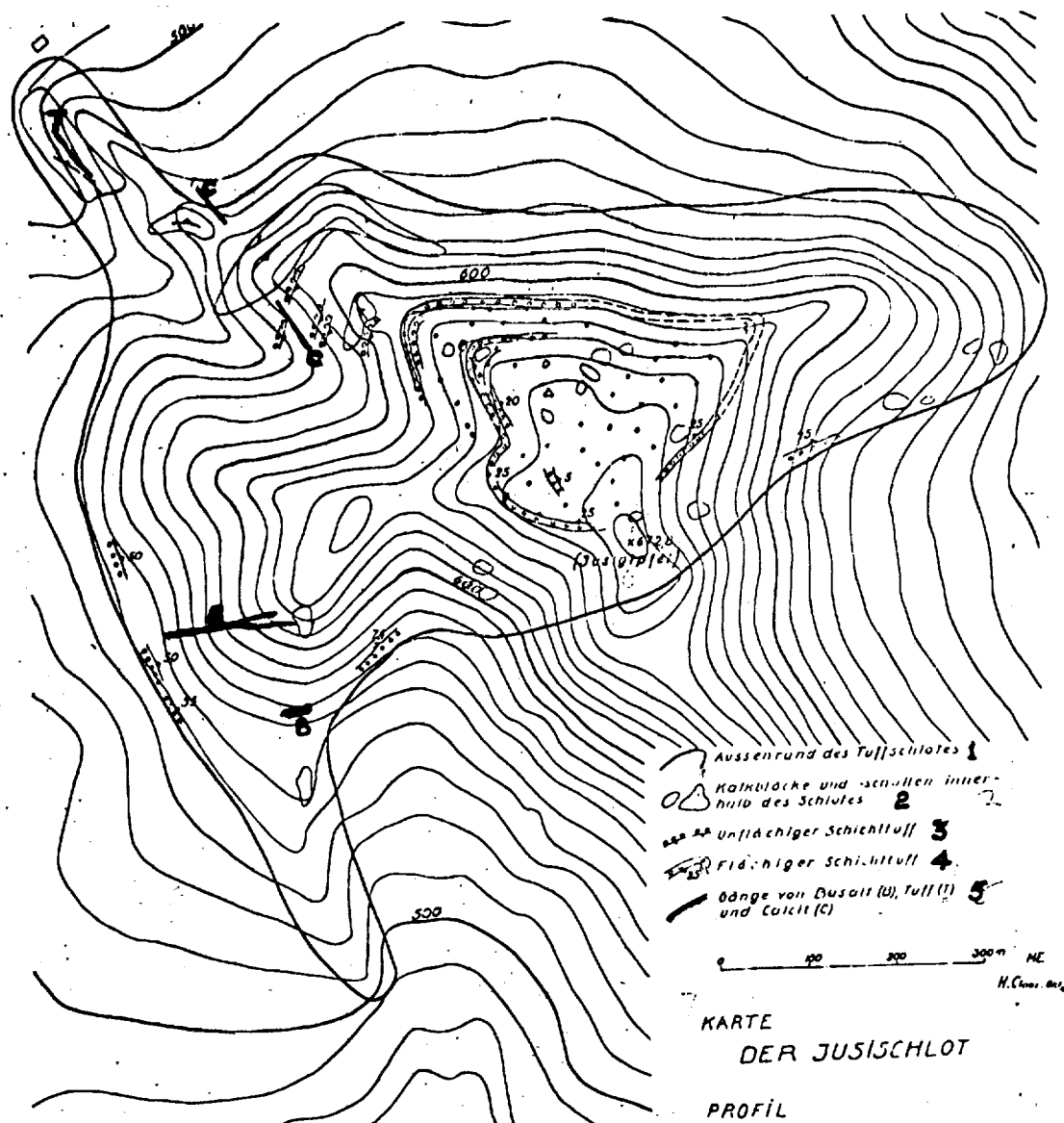
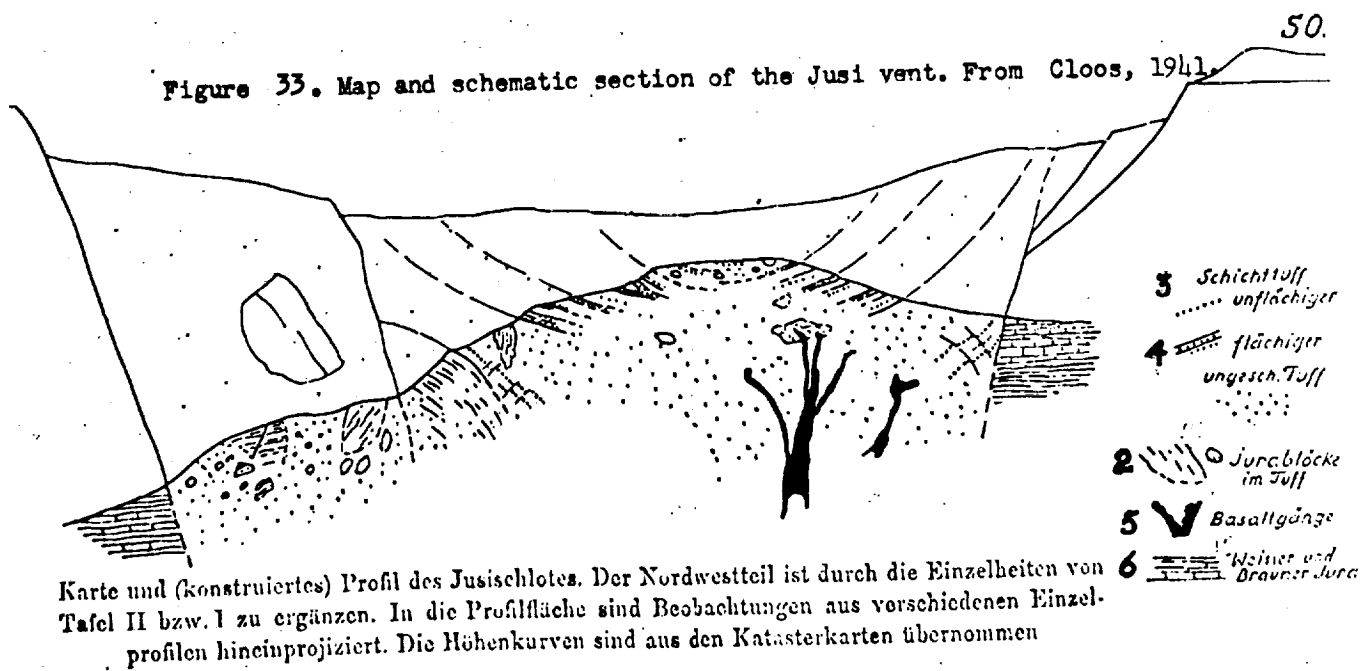


Figure 33. Map and schematic section of the Jusi vent. From Cloos, 1941.



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to its original position, it would occupy more than half of the cross-section of the pipe. We suggest that here, as in the Jusi pipe, the formation of a small vent was followed by a caldera-like collapse of part of the adjoining wall along a ring-fault. Subsequently, ash-laden gases rose along the ring-fault and forcibly injected cracks and joints within the sunken block. Intimate penetration of this kind, if continued for a long time, would remove all evidence of the caldera-like collapse. In any event, the kind of subsidence of wall-rocks in the Eichelberg and Jusi pipes contrasts with that visualized by Cloos in which individual blocks of large size subside slowly in a gas-particle system that rises at very high velocities.

The Metzinger Weinberg pipe, which measures between 300 and 400 m. in diameter, has been eroded to a depth of about 300 m. below the original surface. Bedded pyroclastic deposits close to the walls dip inward at angles of 65° to 80° , indicating strong subsidence of the filling of the pipe. In the small Geigersbühl pipe, which has been eroded to a depth of approximately 600 m., there are blocks of Jurassic limestone that must have subsided about 500 m.

The Bürzlen pipe has been examined in great detail by Papenfuss (1963). Although it measures only 300 m. in diameter, it has been exposed by erosion to a depth of more than 600 m. The filling-material of the pipe is unstratified and homogeneous. Roughly half of the filling material consists of juvenile, magmatic debris; the other half consists of accidental, lithic debris, mainly fragments of Jurassic rocks accompanied by a few of Keuper rocks, but including only rare fragments of crystalline basement-rocks. The magmatic components consist of ash, lapilli, and bombs along

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with discrete crystals of augite, hornblende, biotite, titanomagnetite, and apatite. A K/Ar age-determination on the biotite indicates that the B rzlen pipes is one of the oldest in the Schwabian Alb, having been formed 20.4 m.y. ago.

Study of the grain sizes of the well-mixed pyroclastic material gives a nearly symmetrical distribution with a median diameter of 0.3 mm. and very poor sorting ($Q_3/Q_1 = 2.5$). Two samples weighing almost 60 kg., taken 80 m. apart, gave nearly the same distribution-curves, indicating that homogenization continued to a mature stage. Moreover, the curves resemble those calculated from industrial grinding processes, suggesting that a comparable mechanism was involved in the formation of the fine-grained pyroclastic materials.

In the opinion of Papenfuss, the B rzlen pipe was formed in the following manner. Its position was controlled by structural features within a zone of tectonic weakness, and its initial size and shape were determined during a strong eruptive phase that may have lasted only a few days. During this brief episode, the country rocks within the pipe were brecciated and partly discharged at the surface, but without much juvenile material. A milling process that took place toward the close of this initial phase brought about the grain-size distribution already mentioned. Subsequently or partly at the same time, degassing of deep-seated magma resulted in fluidization of the pipe-filling, so that the lithic and magmatic materials were mixed, and elutriation led to enrichment of fine debris in the upper part. During this phase, little but gas escaped at the surface. Finally, a fixed bed was formed within the pipe, and the filling materials were cemented during the declining hydrothermal phase, mainly by carbonates but

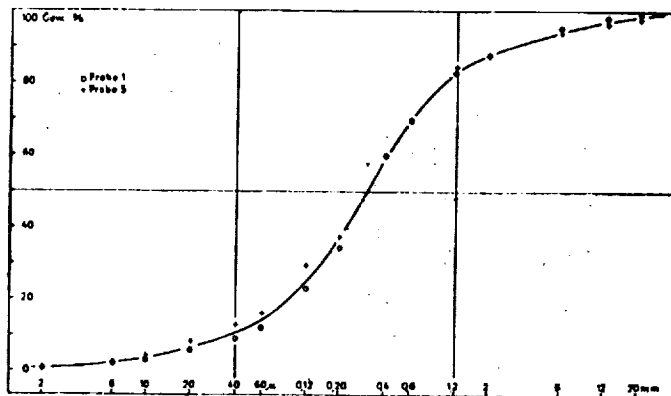


Abb. 82: Kornsummenkurve des Tuffs vom Bürzlen.

Figure 34. Cumulative curve of the tuff in the Bürzlen pipe, southern Germany. (Samples 1 and 5). From Papenfuss, 1963.

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also by the development of montmorillonite.

Papenfuss, it will be noted, thought that grinding preceded mixing and elutriation; in our opinion, however, as in that of Squires (1962), grinding, mixing, and elutriation take place simultaneously during the process of fluidization.

The Hegau Diatremes, Southwest Germany

(von Engelhardt and Weiskirchner, 1961; Weiskirchner, 1967)

Volcanism began in the Hegau area, west of Bodensee (Lake Constance) about 14 m.y. ago and lasted 7 m.y. The parent magma, as in several other Tertiary volcanic fields in Southern Germany, was an alkaline olivine basaltic one. In the Hegau area, this parent magma, through crystal fractionation and reactions with country rocks, gave rise to an unusually wide range of rock-types, from ultramafic, melilite-bearing types through alkali-olivine basalts and intermediate types, including phonolites, to rhyolites. Eruptive activity ranged from voluminous explosions that produced widespread pyroclastic flows (ignimbrites)--the so-called "Deckentuffe"--to the protrusion of viscous lava to form Pelean domes.

Of particular interest in the present connection is the occurrence in some diatremes of juvenile, magmatic lapilli (pellets). In the Junkernbühl pipe, the ellipsoidal, smooth-surfaced lapilli reach a maximum length of 12 mm. Each has a central core, between 0.4 mm. and several millimeters in diameter, consisting either of a juvenile phenocryst or a xenolith. No lapilli contain double cores. The weight-ratio of the core to the surrounding groundmass varies between 5:1 and 1:100. The grain-size distribution corresponds to a Gaussian distribution, denoting a single process of formation; the maximum of the distribution lies at 4 to 6 mm. Sanidine is the predominant mineral of the groundmass, and the laths are arranged tangentially with respect to the surfaces of each lapillus.

In the Lederbohl pipe, no lapilli measure less than 1.2 mm across, and the weight-ratio of core to groundmass ranges from 1:20 to 1:50. Lapilli measuring 3 to 4 mm. across are almost ideally round; smaller and larger lapilli deviate from this shape, though the deviation for larger

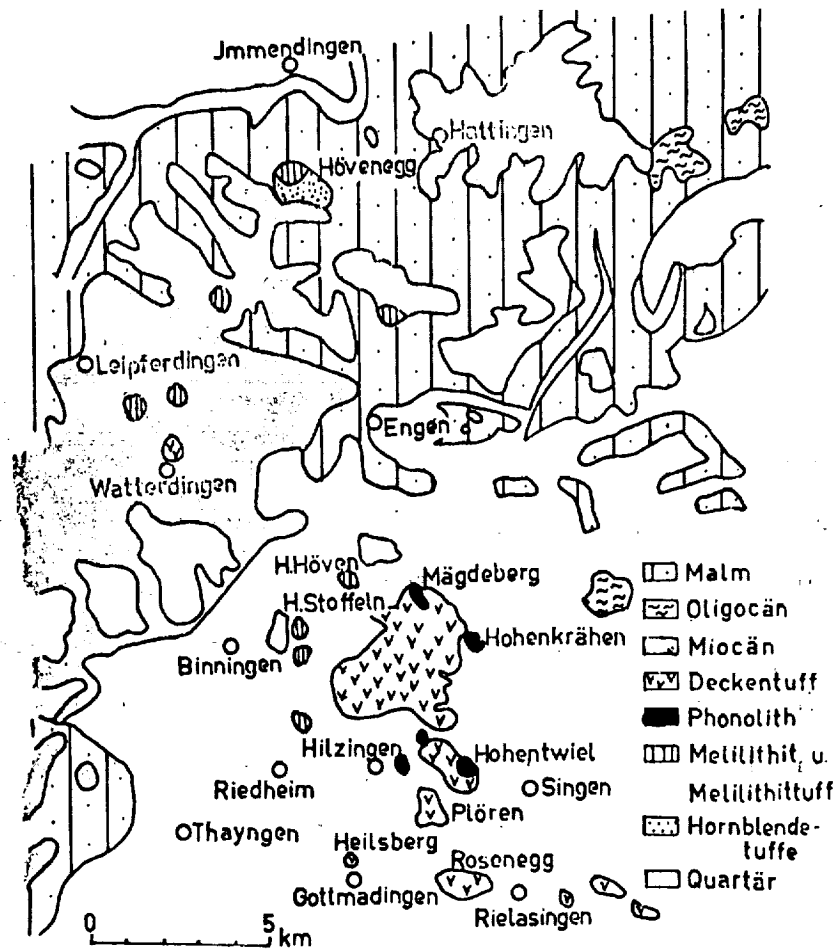


Figure 35. Geologic map of the Hegau. From von Engelhardt and Weiskirchner, 1963.

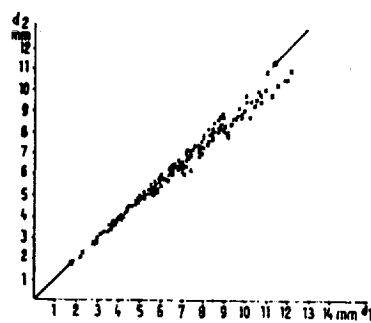


Abb. 18. Größenverhältnis der Lapilli „Lederbohl“

Figure 36. Major and minor diameters of the lapilli from the Lederbohl pipe, Hegau. From Weiskirchner, 1967.

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lapilli is still less than 10 per cent. Presumably large lapilli did not rotate fast enough to produce ideally round shapes, and in smaller lapilli the relatively large cores exerted too much influence. Some lapilli were indented by adjacent ones or by fragments of basement-rocks, indicating that they were plastic when deposited.

In the pipe on the south side of the Hohentwiel, some lapilli of unusually well-developed round shape lack cores.

The origin of the ellipsoidal and round lapilli is assumed to be disruption of gas-rich magma that was sufficiently fluid to form droplets around individual solid particles. While suspended in rising gas, the droplets were shaped by surface tension and rotation.

Diatremes of Northeast Bavaria
(Schröder, 1965)

Approximately 30 pipes and many dikes of alkali basalt of Late Miocene to Plio-Pleistocene age are present in northeast Bavaria. The area is characterized by large-scale faulting of Mesozoic age and by complex faulting and uparching of post-Jurassic age. Basaltic volcanism does not seem to be related to simultaneous tectonic movements; however, pipes developed preferentially in centers of uparching whereas dikes filled tension fissures, using pre-basaltic joint planes. Moreover, the larger the center of uparching, the larger and more numerous are the pipes.

At the time of volcanism, the general surface was approximately 250 m. above the present surface. Some pipes, particularly the small ones, are filled almost, if not entirely, by lithic debris resulting from comminution of wall-rocks; but many pipes with diameters exceeding 120 m. have central cores of intrusive, columnar basalt. Locally, the pipes contain blocks of country-rock up to several tens of meters across; these indicate progressive disruption and brecciation without much transport. Elsewhere, on the contrary, there is evidence of large vertical displacement of fragments, both up and down. An extreme case is to be seen in a small pipe that contains only 1 per cent of magmatic material, in which fragments of Muschelkalk were carried upward about 80 m. to lie next to fragments of Liassic rock that subsided about 500 m.

The outlines of pipes that cut hard rocks reflect the joint-patterns in the walls, whereas those of pipes that cut soft rocks are much more intricate. Progressive disruption of the country rocks along bedding planes and joints and mechanical replacement denotes that the pipes were not formed by violent explosive eruptions but by a more gradual process.

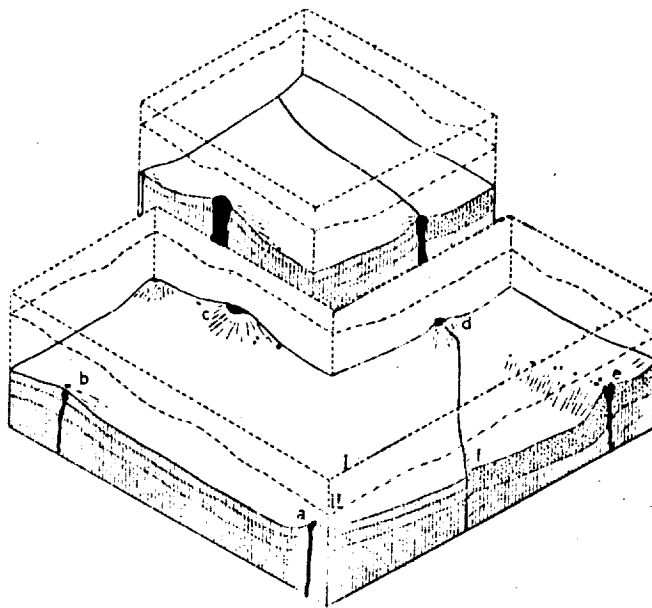


Figure 37. Relationship between tectonic structure and pipes, eastern Bavaria. From Schröder, 1966.

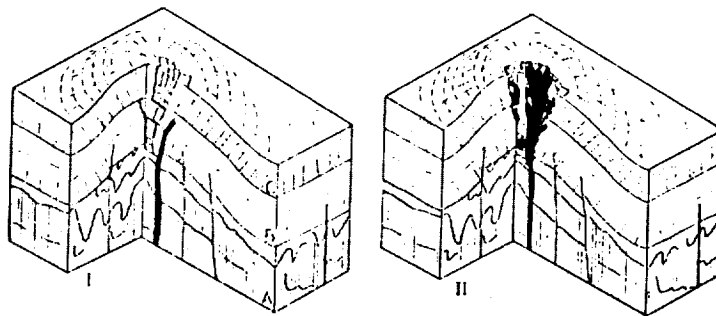


Figure 38. Stages of development of pipes in eastern Bavaria. From Schröder, 1966.

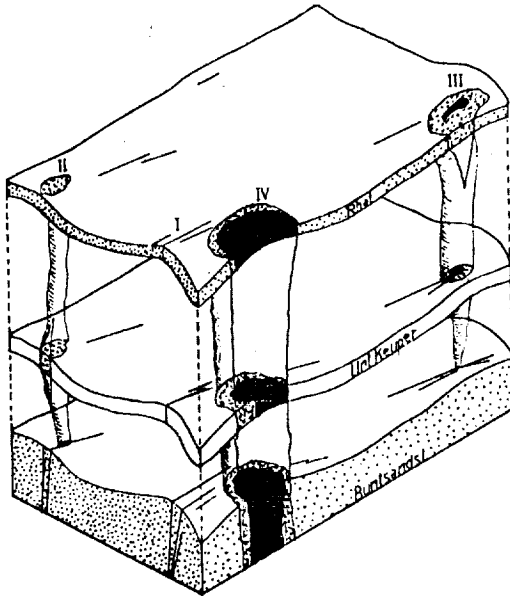


Figure 39. Structural relationship and types of filling of pipes of the Heldburg zone, eastern Bavaria. From Schröder, 1966.

Permian Diatremes in the Saar-Nahe Trough,
Southwest Germany
(Lorenz, 1968)

Nine breccia pipes have been recognized in the Donnersberg area of the Saar-Nahe trough in Southwest Germany. They occur in Lower Permian (Rotliegendes) lake and fluviatile deposits. The area is also characterized by many lavas, sills, irregular intrusions, pyroclastic beds and a large intrusive dome of rhyolite, the Donnersberg, around which all the volcanic rocks are clustered.

The oldest pipes, which are farthest from the rhyolite, contain high-alumina quartz-tholeiite; the younger pipes, which surround the rhyolite dome, contain andesite and rhyodacite. This suggests a genetic relationship between the pipe-magmas and the rhyolite.

Most pipes are oval with their longest diameters oriented either northwest-southeast or northeast-southwest, these being the main structural trends in the area. The longest diameters of the four largest pipes are 1520 (Falkenstein), 1220 (Birnberg), 750 (Rüdern), and 660 m. (Hirschberg).

In seven of the nine pipes there are subaerically deposited pyroclastic beds that must have subsided. Maximum values for the subsidence are several hundred meters to 1.4 km.

The pipe-fillings consist of lapilli tuff with enclosed country rock fragments, large blocks of country rock and intrusions. In the lapilli tuff, juvenile lapilli and comminuted country rock can be distinguished. Under the microscope the former show vesicles, flow-oriented plagioclase laths of (01.-02. mm. long); in the Hirschberg and Rüdern pipes there are also pseudomorphs after olivine, and pyroxene in a groundmass of altered glass. The large blocks of country rock were invariably derived

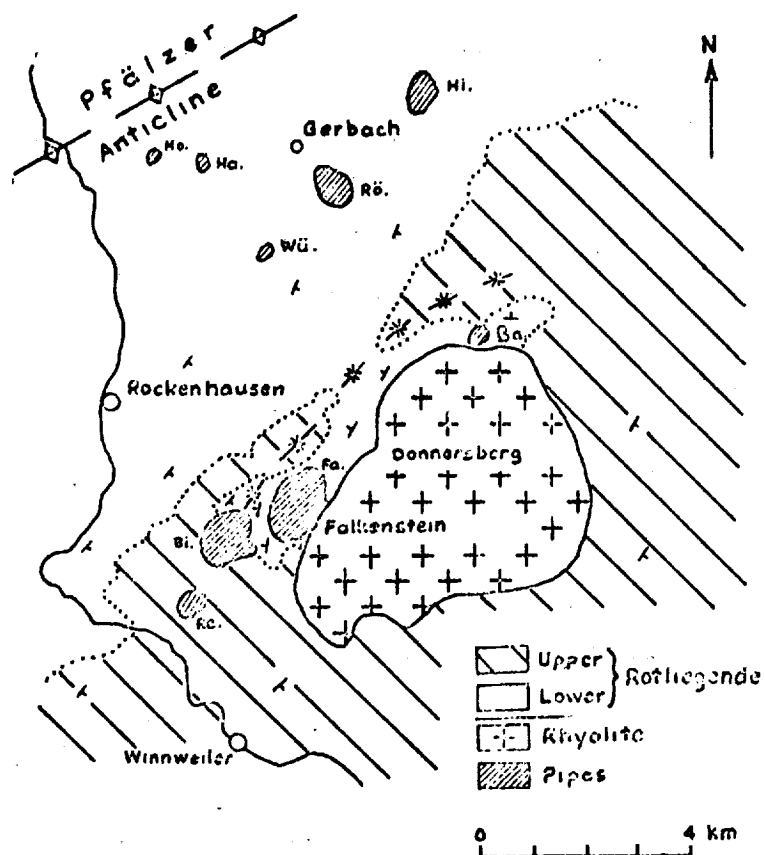


Figure 40. Geologic map of the Donnersberg area, showing location of diatremes, Palatinate, southwest Germany. From Lorenz, 1970.

(Permian Diatremes in the Saar-Nahe Trough)

from horizons higher in the stratigraphic sequence than those in the walls of the pipes at the present surface and therefore must have subsided.

At the Rödern, the northwestern part consists of bedded pyroclastic rocks that overlie an olivine basalt lava. Both the pyroclastic beds and lava dip steeply inward, forming a saucer-shaped structure surrounded by a ring-fault. The southeastern part, the actual feeder, contains unbedded pyroclastic material and large disintegrated blocks of country rock and intrusive basalt.

The following history is suggested: at first fine-grained, well-bedded and later coarser-grained, poorly-bedded pyroclastic ejecta were deposited in the form of a tuff cone or tuff ring more than 150 m. high on the olivine basalt lava that formed the regional surface. Collapse northwest of the feeder along a ring-fault with differential subsidence of 500 to 700 m. produced the saucer-shaped structure in which steeply dipping pyroclastic beds still overlie the lava flow on which they were originally deposited. In the actual feeder, large blocks of country rock subsided individually prior to an en masse subsidence of the whole feeder-filling. Intrusion of basalt into the pyroclastic debris terminated activity.

The Hirschberg structure reveals essentially the same history, but is more fragmented. The amounts of differential subsidence are between 150 and 260 m. After collapse and caving of the upper walls, volcanic activity spread over the whole collapsed area as indicated by partial replacement of country rock blocks near the margins by volcanic breccia. Intrusion of basalt also took place mainly near the margin of the structure along the ring-fault and between large blocks of country rock.

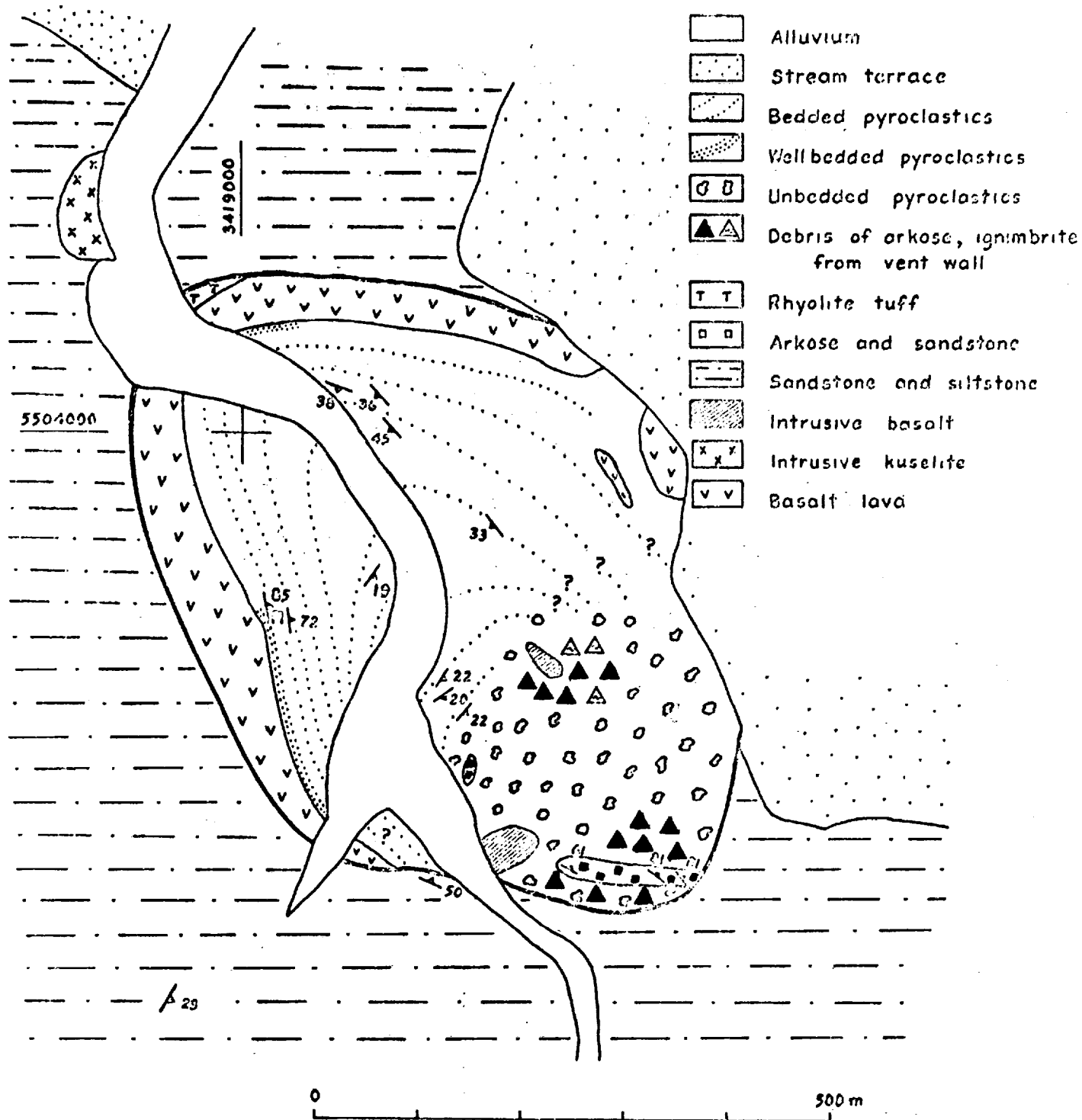


Figure 41. Geologic map of the Rödern diatreme, Palatinate, southwest Germany. From Lorenz, 1970.

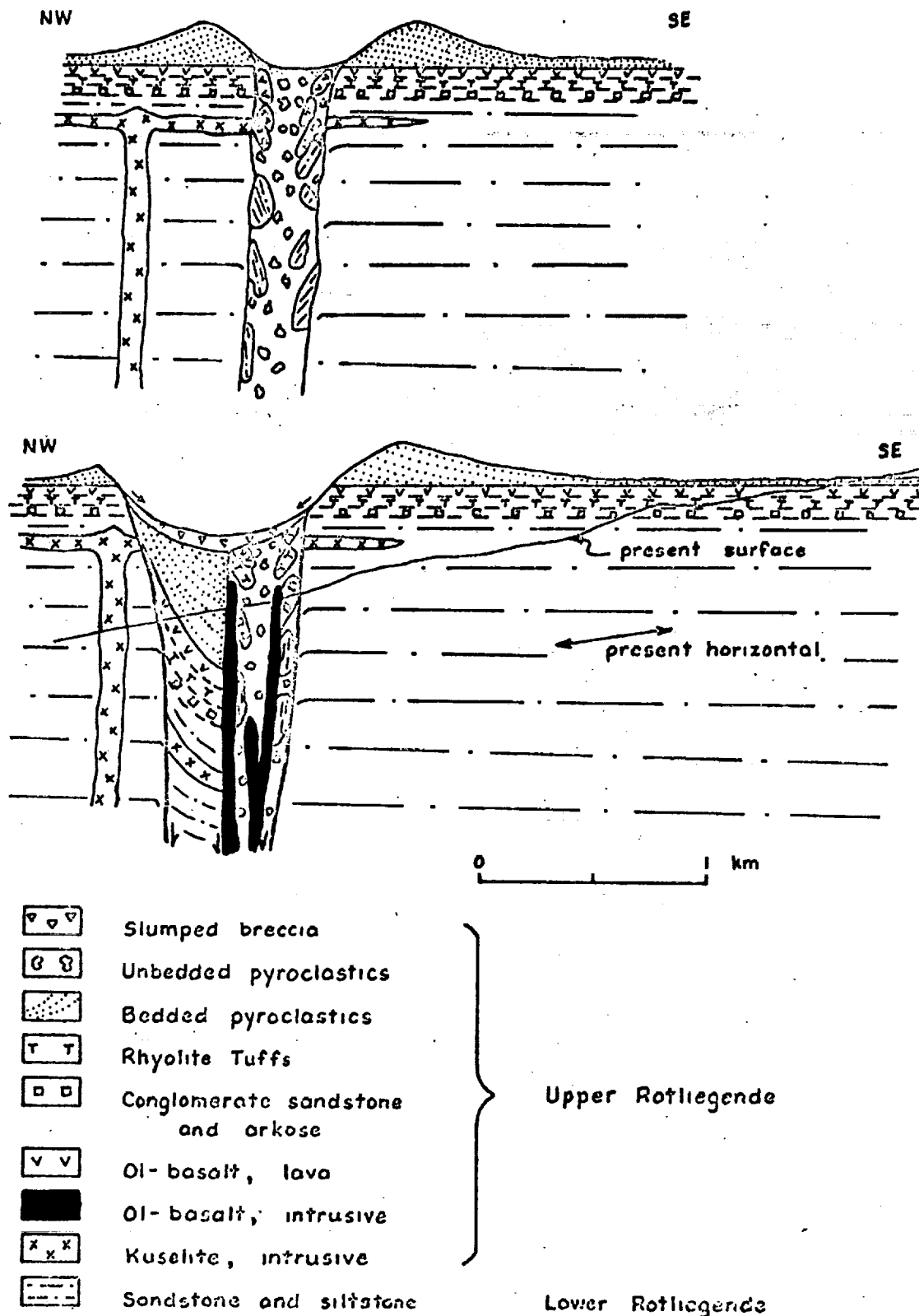


Figure 42. Schematic cross-section through the Rødern diatreme indicating its main stages of development. From Lorenz, 1970.

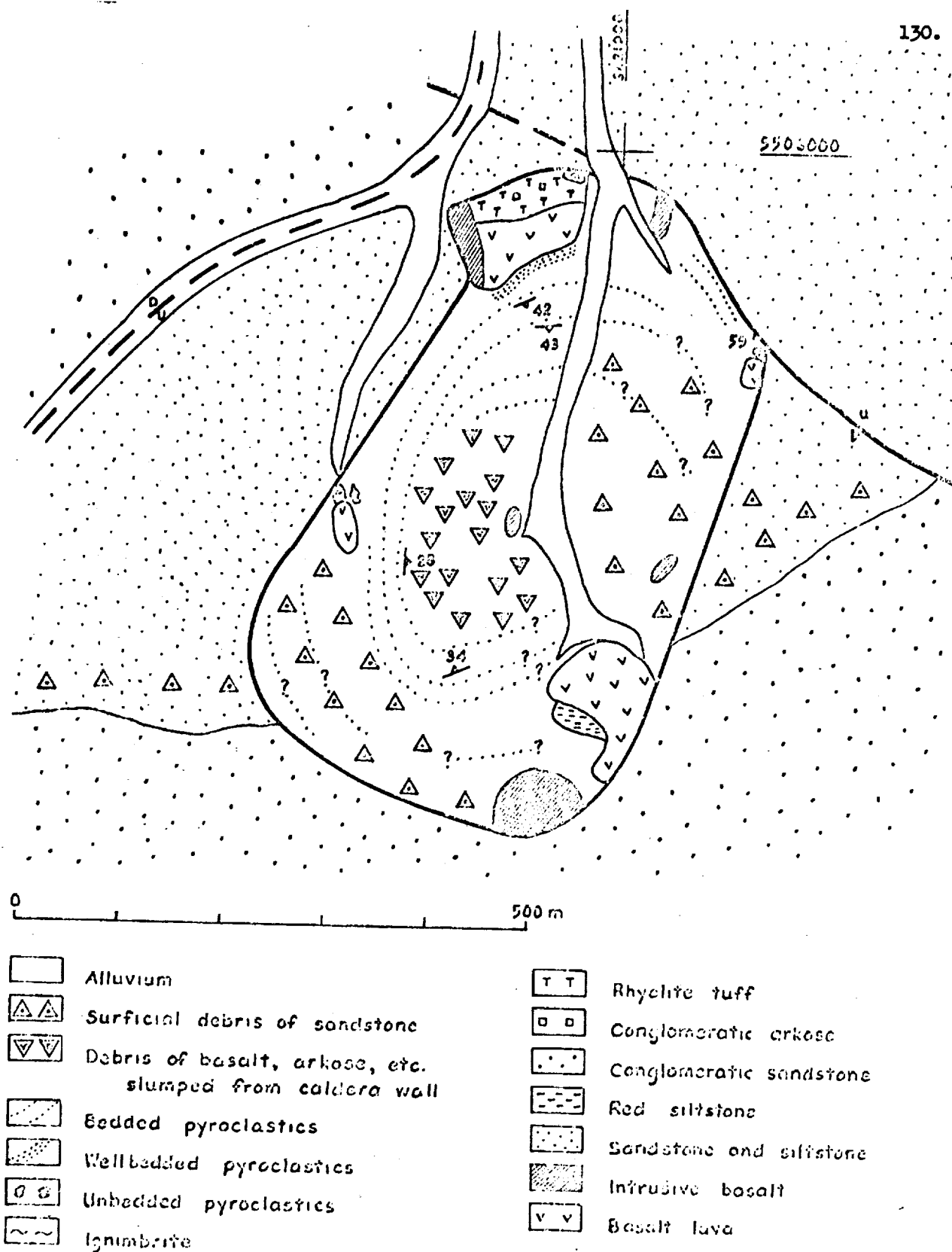


Figure 43. Geologic map of the Hirschberg diatreme, Palatinate, southwest Germany. From Lorenz, 1970.

(Permian Diatremes in the Saar-Nahe Trough)

Several kilometers southeast of the Rödern and Hirschberg, olivine basalt flows are overlain by basaltic pyroclastic beds; both of the same type as in the Rödern and Hirschberg structures.

At the Birnberg, stratified, subsided pyroclastic beds are found near the margin of the pipe whereas the central part is occupied by intrusive andesite. At the top of the Birnberg, the andesite is very vesicular and is assumed to have formed a lava lake within the collapsed structure from which lava flows spread to the northeast and southeast.

The Falkenstein structure is the largest and most complex in the Donnersberg area. About a third of it is occupied by bedded pyroclastic material, a third by subsided blocks of country rock, and a third by intrusive rhyodacite. Bedding in the pyroclastic ejecta and subsided blocks of sediments are mostly oriented toward the center of the structure. At two localities outcrops of unbedded pyroclastic material show homogeneous, well-mixed lapilli tuff with a regular distribution of several large rhyodacite and basalt blocks. This indicates that the pyroclastic ejecta occupy feeder-pipes. Several large blocks of country rock are intruded or brecciated and partly replaced by breccia containing juvenile lapilli.

The sequence of events started with eruption of pyroclastic materials and local intrusion of rhyodacite. Renewed eruptions led to deposition of pyroclastic beds containing ejected blocks of shattered early rhyodacite. Collapse of a large area round the original feeder fragmented the substrata and destroyed the surface structure. Differential subsidence due to drag along the ring-fault produced the inward dip of both country rock blocks

and bedded pyroclastic ejecta. Rhyodacite then intruded large areas of the fragmented collapse structure. Renewed gas activity formed at least two new feeders and locally destroyed the bedding of the surrounding pyroclastic deposits. Some large blocks of country rock were intruded and partly replaced by breccia. Near the center of the largest intrusive rhyodacite complex, even rhyodacite was brecciated and fragments now imbedded in a fine-grained matrix were rounded by a milling process due to fluidization by gas.

Even pipes eroded to depths of 1100 to 1400 m. contain bedded pyroclastic deposits assumed to have been laid down at the surface.

Structures just described must have terminated upward in quite large maars or small collapse-calderas with diameters of several hundred to more than 1500 meters.

Diatremes in Northwestern Bohemia, Czechoslovakia

(Kopecký, et al., 1967)

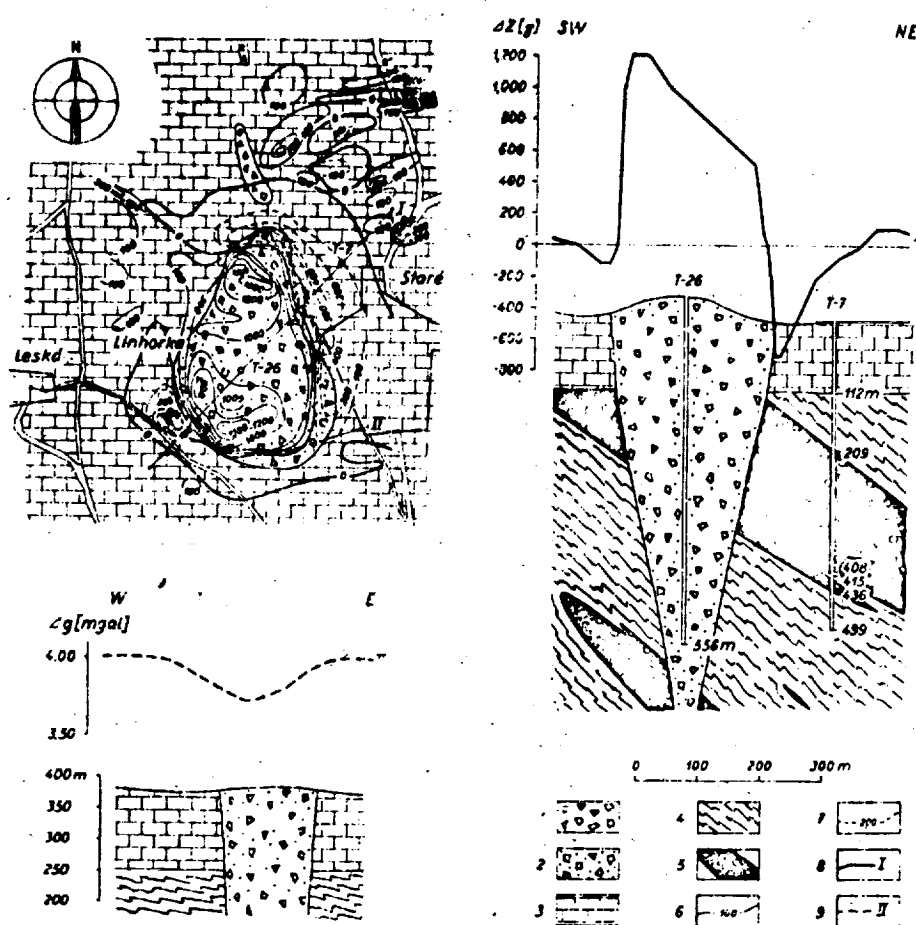
The České Středohoří Mountains of northwestern Bohemia contain many Miocene and Pliocene diatremes arranged along the margins of a volcano-tectonic belt. Extensive investigations, including drilling and geophysical surveys, have recently revealed interesting results.

The diatreme-area consists of a basement of orthogneisses, two-mica-garnetiferous gneisses, migmatites, pyrope-bearing peridotites, and granulitic gneisses overlain by Carboniferous and Cretaceous sediments that carry detrital grains of pyrope. Tertiary beds, including diatomaceous earths, occur locally. The present erosion-surface lies approximately 400 m. beneath that which obtained when the diatremes were formed.

The pipes vary in plan from circular to oval to irregular. Their diameters range from 75 to 1,000 m., generally diminishing at depth. Many pipes occur in groups, the distribution of which, like that of the associated dikes, is controlled by regional structures, and the major axes of elongate pipes generally trend northeast-southwest in common with the dominant structural trend.

The fillings of the pipes consist typically of a brecciated mixture of juvenile and lithic materials, but locally the breccias are cut by massive intrusions. Pipes almost wholly occupied by massive igneous rock show narrow rims of vent-breccia. The composition of the juvenile materials varies, rock-types including leucitites, nephelinites, sodalite tephrites, sodalite-nepheline basalts, limburgites, and olivine basalts. All are largely altered to montmorillonite.

Foreign, lithic debris was derived from the upper mantle, metamorphic basement-rocks, and the sedimentary cover. Fragments of garnetiferous



11. Geological and magnetometric map and gravity profile of the Linhorka diatreme near Staré (L. Kopecký - L. Pokorný 1964)

1 — Pyrope-free vent breccia; 2 — pyrope-bearing vent breccia; 3 — Upper Cretaceous (Cenomanian—Coniacian) sedimentary rocks; 4 — granulite, granulitic gneiss; 5 — serpentinized pyroxene-pyrope peridotite; 6 — $\Delta Z(+)$; 7 — $\Delta Z(-)$; 8 — line of geomagnetic profile and geological section; 9 — line of gravity profile and geological section

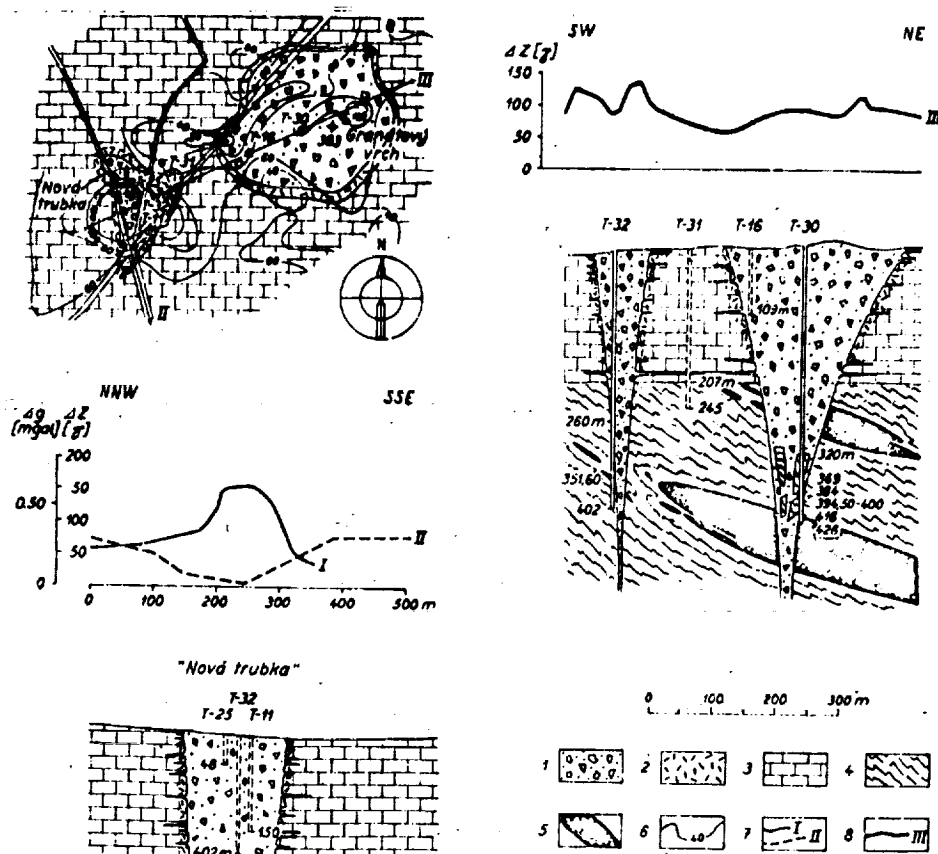
Figure 44. Geologic and geomagnetic map and gravity profile of the Linhorka diatreme near Staré. From Kopecký, et al, 1966.

peridotite containing chrome-diopside and picotite occur within basaltic dikes and as xenoliths exhibit basaltic shells. Other lithic debris of deep-seated origin included serpentized pyroxenes, pyrope-bearing peridotites, granulites, and eclogites. Foreign minerals consist mainly of varicolored garnets derived from Carboniferous and Cretaceous sediments.

Xenoliths from deep sources are generally small, none exceeding 60 cm. across, whereas xenoliths derived from shallower levels may reach several tens of meters across. Fragments of Tertiary clay have been found in some pipes 700 m. below their original level of deposition.

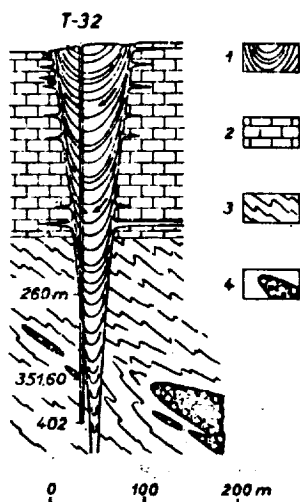
At the margins of the pipes, there is usually a zone, from several meters to 50 m. wide, of contact-breccias consisting of an intricate mixture of pyroclastic debris and shattered wall-rocks. Within these contact-zones, sills of breccia extend outward from the diatremes into the marls, sandstones, and diatomaceous earths of the walls in a manner that suggests the wall-rocks were split along bedding planes by the pressure of vapors generated by heating watersoaked sediments. It is apparent that in these Bohemian pipes, as in the Schwabian pipes, vents were not opened by violent eruptions but by a gradual, penetrative process of brecciation.

In some pipes, the breccias exhibit inward dips due in part to original deposition in the craters of maars and in part to later subsidence. Veinlets of calcite exhibit a similar orientation.



12. Geological and magnetometric map and gravity profile of "Nová trubka" and "Granátový vrch" diatremes near Měrunice (L. Kopecký - L. Pokorný 1964)

1 — Pyrope-bearing vent breccia; 2 — crushed zone of Cretaceous sediments; 3 — Upper Cretaceous (Cenomanian—Coniacian); 4 — granulite and granulitic gneiss; 5 — serpentinized pyroxene-pyrope peridotite; 6 — $\Delta Z (+)$; 7 — line of gravity profile and geological section; 8 — line of geomagnetic and geological profile



6. The structure of "Nová trubka" diatreme near Měrunice, filled with vent breccia (L. Kopecký 1966)

1 — Vent breccia with carbonate fillings of fissures; 2 — Upper Cretaceous (Cenomanian—Coniacian); 3 — granulite and granulitic gneiss; 4 — lenticular bodies of pyroxene-pyrope peridotite

Figure 45. Geologic and geomagnetic map and gravimetric profile of Nova trubka and Granatovy vrch diatremes near Merunice. From Kopecky et al, 1966.

Figure 46. The structure of Nova trubka diatreme near Merunice. From Kopecky et al, 1966.

Carboniferous Volcanic Vents of Scotland

(Cumming, 1936; Geikie, 1897, 1902; Francis, 1959, 1960, 1960A, 1961, 1962, 1962A, 1967, 1968, 1968A, 1969; Whyte, 1964, 1966)

There are few regions in which one can view a more varied and instructive suite of volcanic pipes than in Scotland. In addition to the well known Tertiary volcanic centers of western Scotland there is an older belt of Carboniferous intrusions, lavas, and related vents that crosses Scotland along the Midland Valley. Many of these features were described in the classic works of Geikie (1897, 1902).

Francis (1968) has shown a clear relationship between the rates of sedimentation and the nature of the contemporaneous igneous activity. In regions in which there was little or no sedimentation, ascending magma was able to reach the surface and form extensive lava fields; where thick sequences of weakly consolidated sand, silt, and clay were being laid down, the magma was injected as sills and in many places caused phreato-magmatic eruptions through vents with shallow roots. The relations are in accord with the principles governing the intrusion of sills as stated by Bradley (1965).

An unusually good example of an explosive vent related to a sill has been described from the Bogside coal mine in West Fife (Francis, 1959, 1968). The record of the region is unusually complete, because the activity occurred during deposition of coal measures which have been extensively mined and are known in great detail. The breccia pipe cuts a series of siltstones and shales with interbedded coal seams. The surface at the time of the eruption is marked by beds of tuffaceous sandstone that are related to a rim of low relief surrounding the vent. At

the level of eruption the vent has an elliptical cross section of about 150 by 300 meters. The walls daper downward toward a focus near the top of a dolerite sill which has been shown by boreholes to underlie the vent at a depth of about 600 meters (figure 47). The vent was probably formed when the temperature of water in the sediments overlying the intrusion was raised until an unstable condition was reached and a steam-blast eruption occurred. We have discussed the nature of this process in more detail in an earlier section of this report (p. 19).

Some of the best exposures of Carboniferous vents are along the sea coast of eastern Fife north of Edinburgh. The level of erosion is now about two hundred feet below that at which sedimentation was taking place at the time that igneous activity was taking place. Nearly every stage in the development of the pipes can be seen within a relatively short distance along the shore. The first stage is represented by ill-defined zones of disoriented blocks lying almost in situ. In places, fine tuffaceous material has penetrated between the blocks. The fragmentation seems to have occurred in advance of a rising magma column, but it is difficult to determine whether the disruption was produced by downward propagation of a surface explosion or by disruption of the roof overlying a vertical intrusion. Some of the brecciated zones may not have extended down as far as the magma source, because they have no volcanic material between the blocks, at least at the present level of exposure.

The more mature vents are filled with igneous and sedimentary breccia. Sedimentary material is often the main constituent of the outer parts of the pipes; in a few places it can be shown to have come

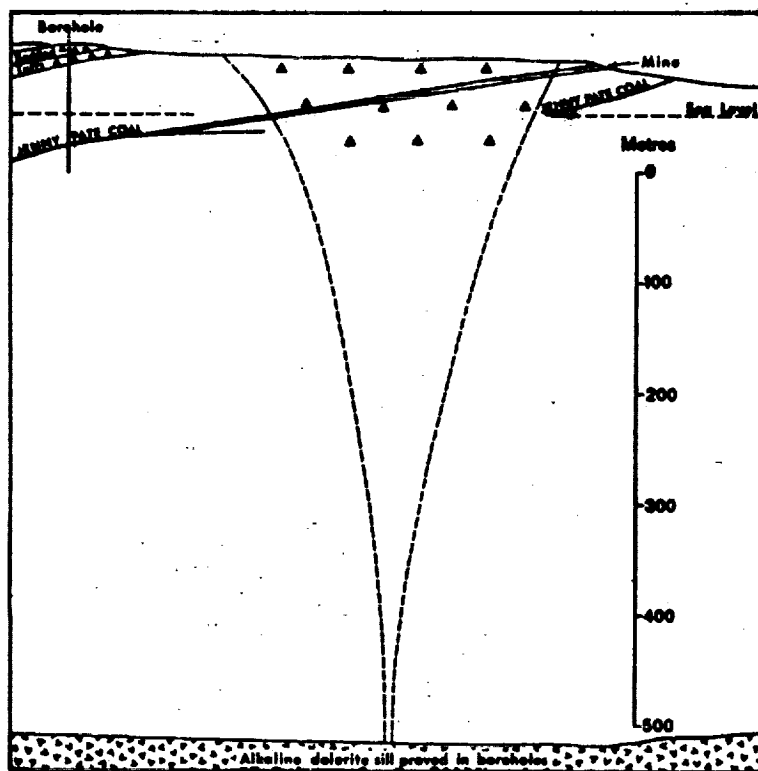


Fig. 47. Horizontal section based on boreholes and mining operations in West Fife, showing relationship between the Bogside Neck and an alkaline dolerite sill at depth beneath. Inclinations of the walls of the neck suggest point source on the roof of the sill. (after Francis, 1967).

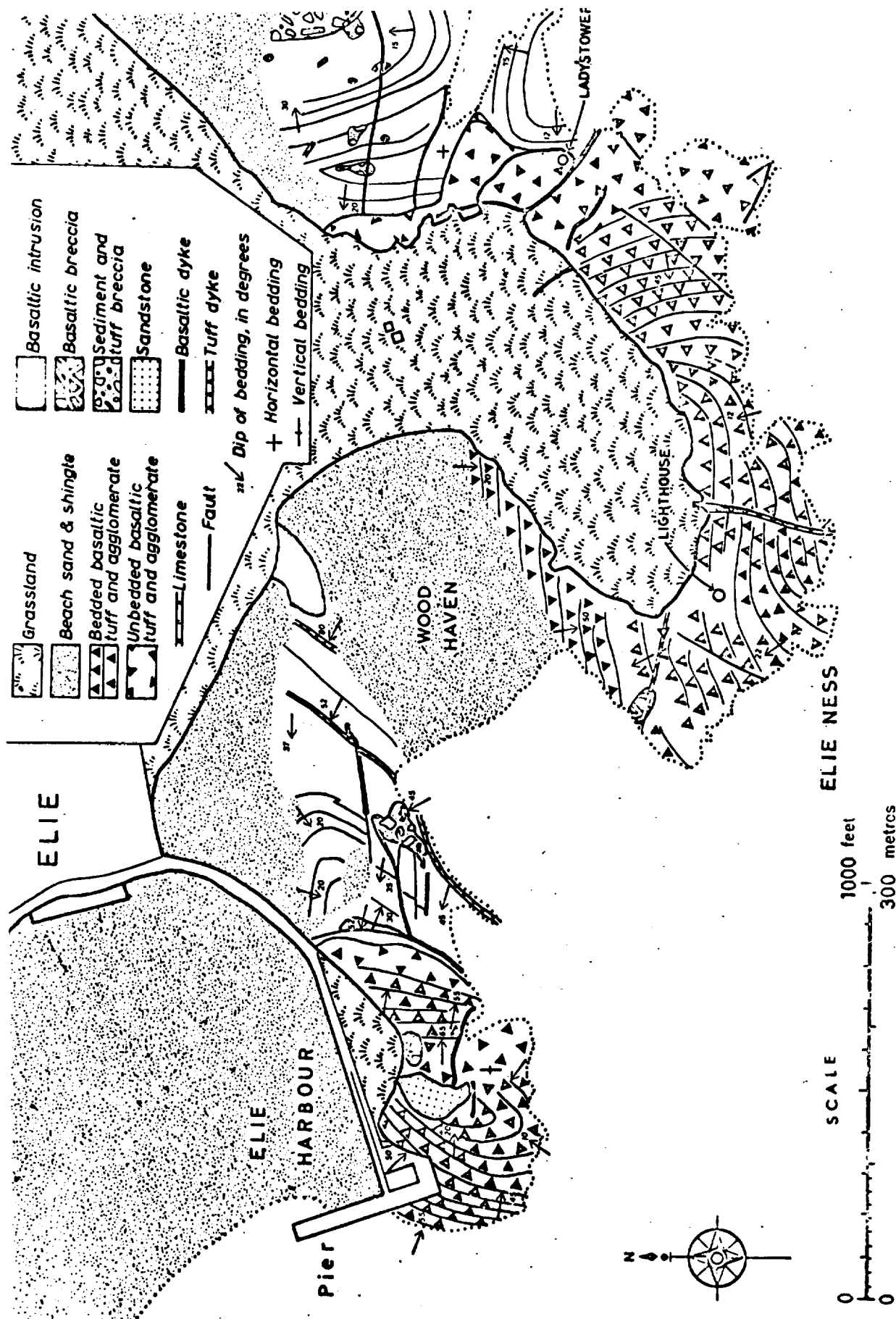


Fig.48. Elie Harbour and Elie Ness necks, East Fife. (after Francis, manuscript, 1970)

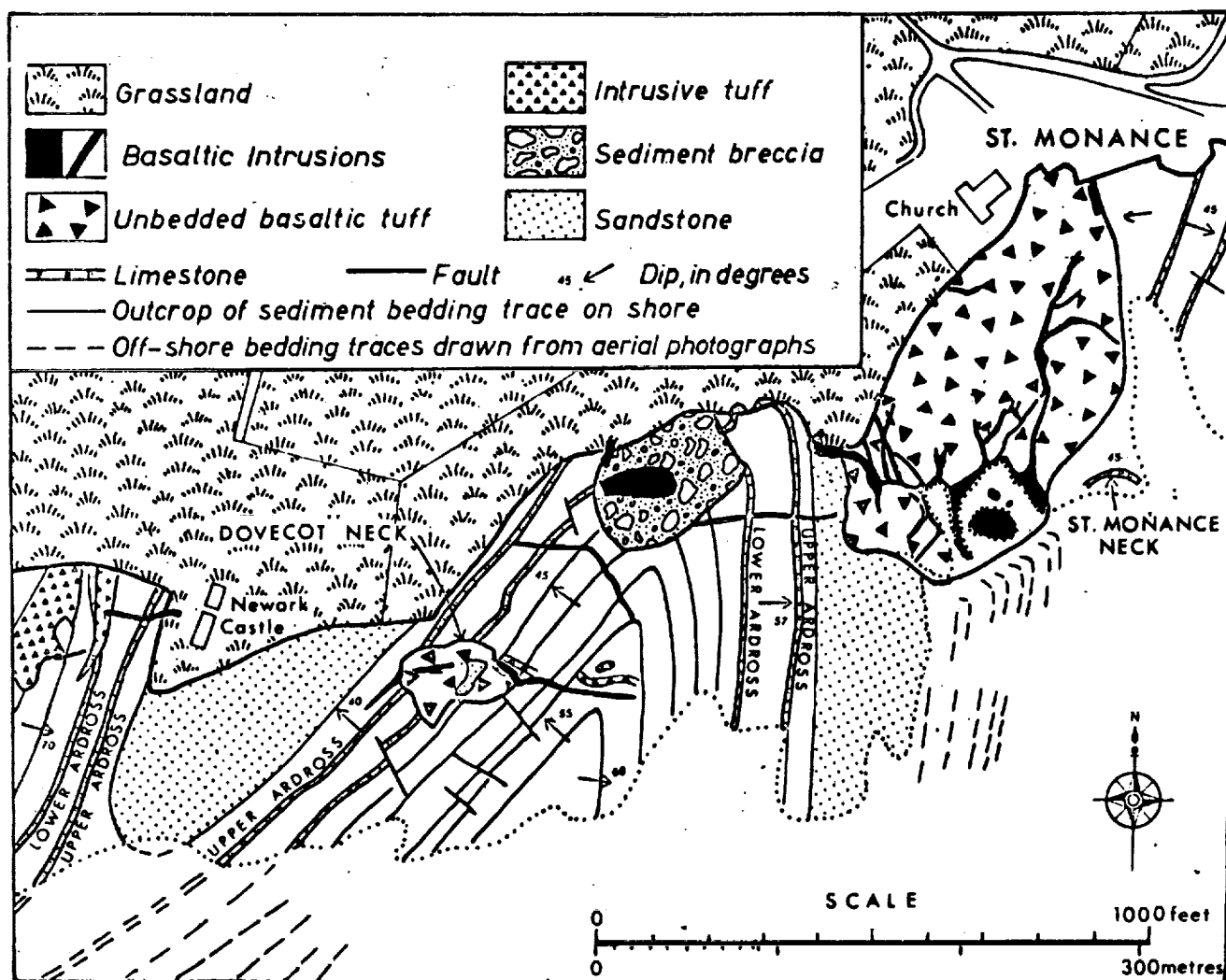


FIG. 49.

Fig. 49. Dovecot neck and St. Monance neck, East Fife. (after Francis, manuscript, 1970).

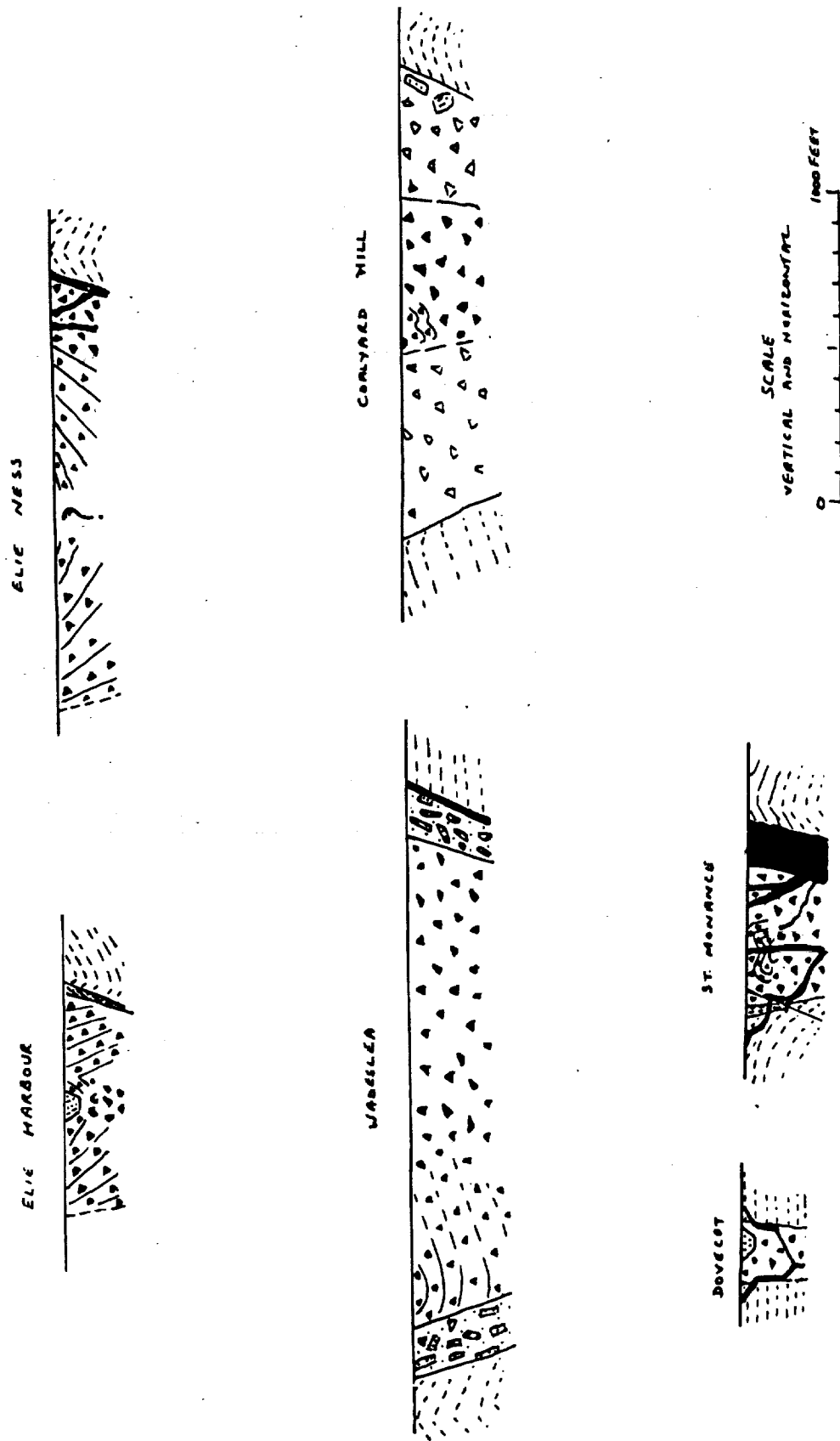


Fig. 50. Cross-sections through necks along the coast of East Fife. (after Francis, Manuscript, 1970)

(Carboniferous Volcanic Vents, Scotland)

from adjacent wall rocks, but more commonly it has been displaced vertically and a zone of shearing separates the breccia from the walls of the vent. Igneous rocks are more abundant in the central zones.

Textural and grain-size variations and differences in the composition of the fragmental debris define conspicuous layers in many of the breccias. The layering normally dips inward at the margins, and toward the center it becomes flatter and less distinct. It is thought that the layering was produced by bedding of subaerially deposited pyroclastic material. Among the features supporting this interpretation are the impact sags in the layers beneath large blocks. In order to have reached its present level, the layered breccias must have subsided along the sheared wall-rock contacts. Similar relations have been described for the vents of western Scotland (Whyte, 1964, 1966). The central portion of the pipes is commonly rich in igneous rocks, both fragmental and intrusive. The fragmental rocks are angular and although they are moderately vesiculated, most were probably solid at the time they were emplaced. The intrusive rocks form irregular dikes and plugs that cut both the breccia and the surrounding wall rocks. One of the dikes contains nodules of pyroxene, olivine, and hornblende, presumably derived from a much deeper level, but there are no recognizable basement rocks that can be correlated with stratigraphic levels much below the known Carboniferous sequence.

Various types of intrusive tuffs are associated with the pipes. As described by Francis (1960, 1962, 1968) some of the tuffs form small dikes, sills, and irregular veinlets cutting through the sedimentary

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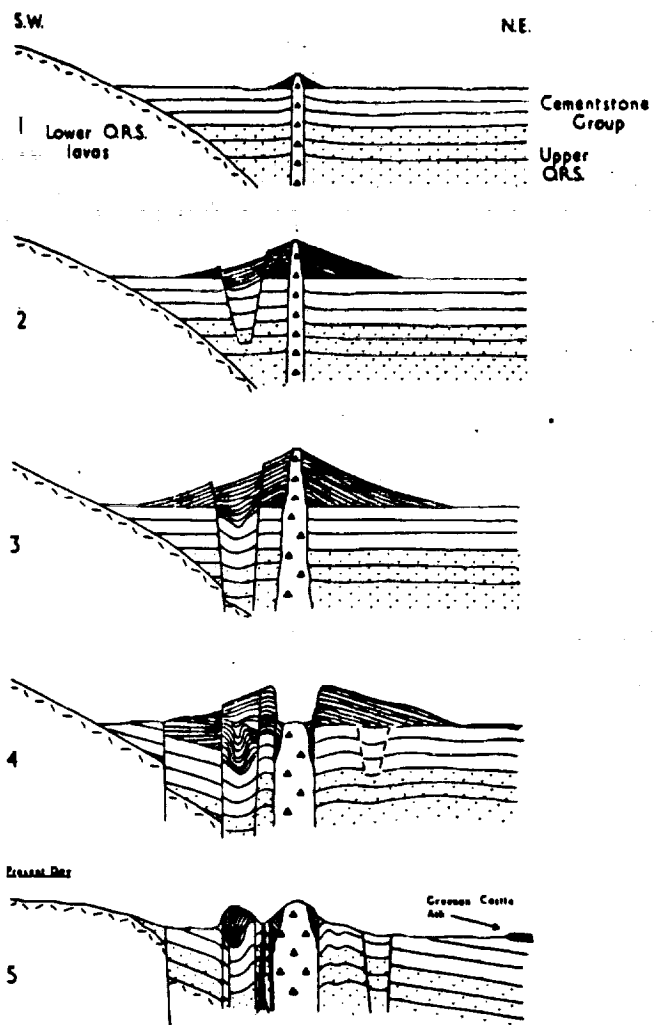


Fig. 2.—Stages in the development of Heads of Ayr vent (not to scale).

Fig. 51 Stages in the development of Heads of Ayr vent. (after Whyte, 1964).

(Carboniferous Volcanic Vents, Scotland)

rocks; others fill narrow spaces between blocks of sedimentary rock. The composition of the tuffs varies between wide extremes. Many consist entirely of sedimentary material, while others contain differing amounts of volcanic fragments, most of which are in advanced stages of alteration and replacement by carbonates and serpentine.

Various origins have been attributed to the tuffs. Geikie (1902, p. 239-276) thought that although a few of the cross-cutting tuffs were intrusive, most were formed when volcanic dust and mud fell back into contraction fractures. As Francis points out, the banding of many of the tuffs parallel to their walls does not support such an origin. Cumming (1936) noted the proximity of the intrusive tuffs to contemporaneous faults and suggested that they were injected as earthquake dikes during sudden movements of the nearby faults. Although this may well be the origin of some of the dikes, it cannot explain all the intrusive features. Most likely, a number of mechanisms have probably contributed to the variety of observed relations. In many places where the tuff consists entirely of sedimentary material it can be seen that the particles of the tuff are derived from immediately adjacent wall rocks and were not injected from an outside source. In these instances, the sedimentary rocks were probably fractured, possibly as a result of an earthquake or heating by a nearby intrusion, and the sudden decrease of pressure caused an expansion of pore water and a break-down of the sediments in which it was contained. In other places, however, the sedimentary material is intimately associated with igneous rocks. Francis pointed out to us an

(Carboniferous Volcanic Vents, Scotland)

unusually interesting locality where a basaltic dike that had intruded the sediments had disintegrated along its margins and was thoroughly mixed with clay, sand and silt. The wall rocks must have lost most of their mechanical strength as a result of the disruption of the walls, because the still-fluid interior of the basaltic dike sagged under its own weight.

Most of the features of the intrusive tuffs seem to indicate that their behavior was governed by the low strength of the sediments at the time of intrusion and by the abundance of groundwater that expanded on heating and fluidized the solid particles. It seems unlikely that the temperature of many of the intrusive tuffs was high, because there are many that contain fragments of coal showing few if any thermal effects.

Diatremes of the Navajo-Hopi Country

(Williams, 1936; Hack, 1942; Shoemaker, 1955, 1956, 1962; Appledorn and Wright, 1957; McBirney, 1963; Malde and Thaden, 1963; McGetchin, 1966)

1. Distribution. No region in the world contains more diatremes in an area of comparable size than does the Navajo-Hopi country of Arizona, New Mexico, and Utah. And the most dense cluster in this country is the southernmost, that of the Hopi Buttes where 300 diatremes are present within an area of approximately 2,500 km². The Navajo cluster, chiefly in the northeast corner of Arizona, contains far fewer diatremes and these are scattered over a much wider area (figure 52).

The diatremes seem at first sight to be distributed at random; closer study shows, however, that many of them, particularly within the Hopi cluster, are alined and elongated in a northwest-southeast direction, parallel to most of the associated dikes and to the predominant joint system in the surrounding sedimentary rocks. Dikes in the Navajo cluster show a similar orientation; however, several of the diatremes are alined at right angles, parallel to the regional strike and the trends of monoclinial flexures. No dike or diatreme seems to be localized by a fault.

2. Age and mode of occurrence. The Hopi diatremes were formed during Middle Pliocene time in a region of low relief marked by swamps, marshes, and wide floodplains, and no doubt many of them terminated at the surface as low, conical islands of ejecta within the Pliocene Hopi Lake. The Navajo diatremes were probably formed at about the same time, but in a region of considerably greater relief. Indeed, locally, as on the present site of the Chuska Mountains, the pre-volcanic relief was almost 350 m. In

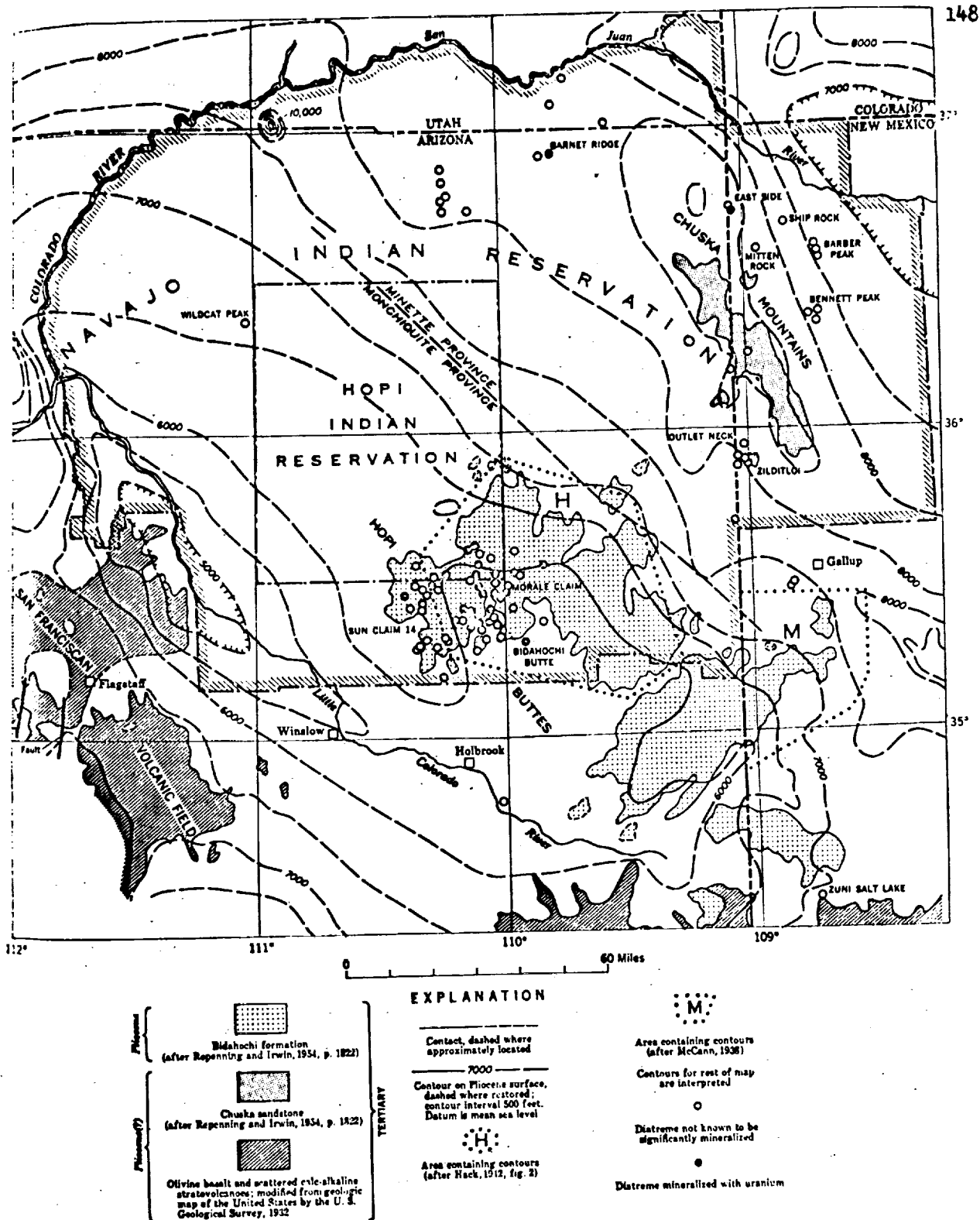


Figure 52. Diatremes, sedimentary and volcanic rocks of Pliocene age in the Navajo-Hopi country. Contours are on the Pliocene surface. From, E. M. Shoemaker, 1955.

(Diatremes of the Navajo-Hopi Country)

both the Hopi and Navajo regions, however, most of the near-surface sedimentary rocks must have contained abundant groundwater at the time they were pierced by the diatremes. Erosion has long since removed the near-surface parts of the diatremes and the maars that were formerly present. Some diatremes, such as Ship Rock and Agathla in the Navajo cluster, are exposed over a vertical distance of approximately 400 m., but the tops of almost all lie a few hundred meters below the middle Pliocene surface. However, the Mule Ear and Moses Rock diatremes, according to McGetchin, are now exposed at least 900 m. below the eruption-surface.

3. Shapes and sizes. The typical Hopi and Navajo diatremes are roughly circular or oval in plan, but many have intricate outlines, particularly where their walls consist of intensely fractured sandstone. Some markedly elongate diatremes are simply the wide parts of dikes; others are themselves breccia dikes, such as the Moses Rock dike, near Mexican Hat, Utah, which is exposed over a length of more than 7 km., with a maximum width of 300 m.

The walls of most diatremes flare upward. Where those of the Hopi diatremes cut Mesozoic rocks, they dip inward at angles of more than 45° , but where they cut the softer, overlying sediments of the Tertiary Bidahochi formation their inward dips are lower. Hack says that Hopi diatremes exposed at high level range in diameter from about 900 to 1,200 m., whereas at deeper levels they measure about 150 to 900 m. across. Shoemaker (1962) says that their diameters at the level of the White Cone Member of the Pliocene Bidahochi formation range from a few hundred meters to approximately 3 km.

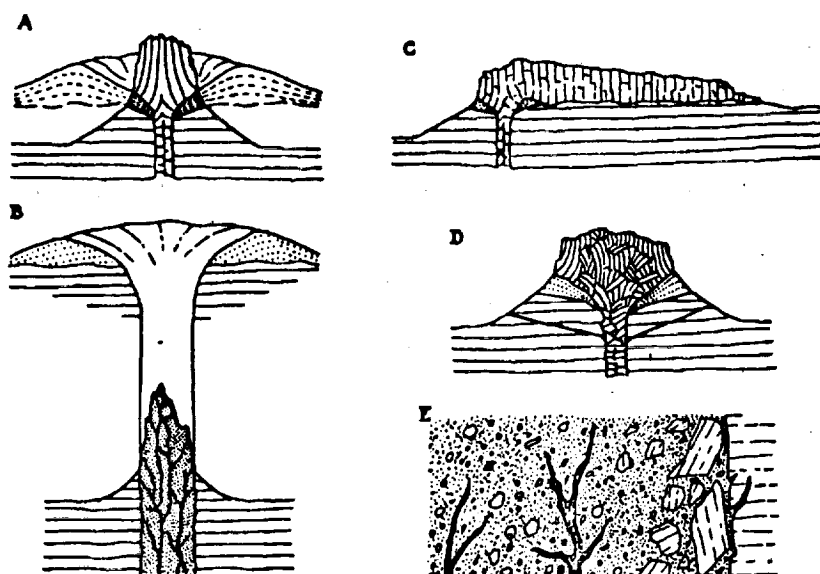


FIGURE 4.—Diagrammatic sketches of Navajo-Hopi necks

(A) Common type of Hopi neck. Diverging columns of lava resting on inward-dipping tuffs and surrounded by undeformed Mesozoic sediments. Possible form of original crater is suggested.

(B) Common type of Navajo neck, Agathla. Shaft of tuff-breccia riddled with dikes of minette. Conduit probably terminated at surface in an explosion pit or maar.

(C) Lava spilling from a Hopi vent.

(D) Neck forming Smith Butte, Hopi Buttes. Flat-lying Chinle shales; inward-dipping tuffs of crater, enclosing columnar lavas due to several upwellings into crater; cone sheets.

(E) Margin of typical Navajo neck. Fractured walls of sandstone (right), detached blocks, lying in a matrix of comminuted minette and sediments (left). Later dikes of minette.

Figure. 53. Diagrammatic sketches of Navajo-Hopi diatremes.

From Howel Williams, 1936.

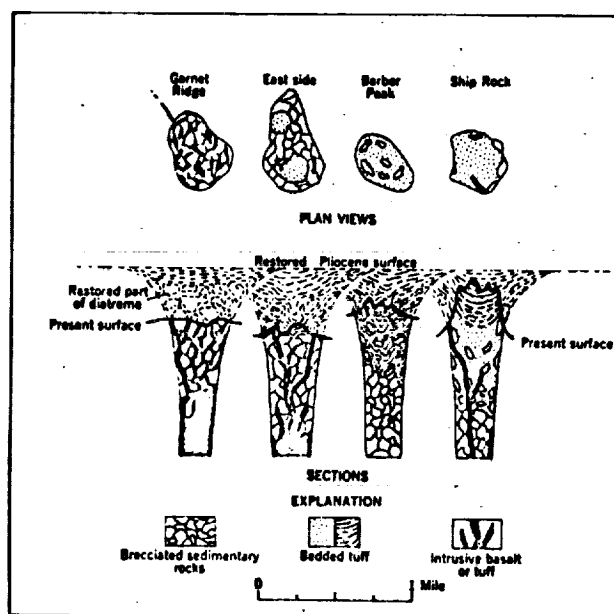


FIGURE 35.—Diagrammatic plan views and sections of four diatremes from the Navajo Reservation illustrating successive stages of subsidence.

Figure 54. Diagrammatic plan and sections of four diatremes from the Navajo Reservation illustrating successive stages of subsidence. From E. M. Shoemaker, 1955.

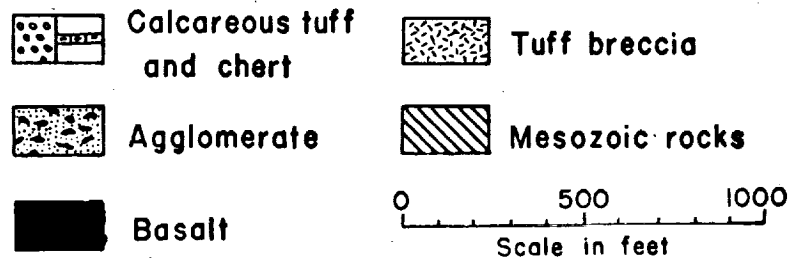
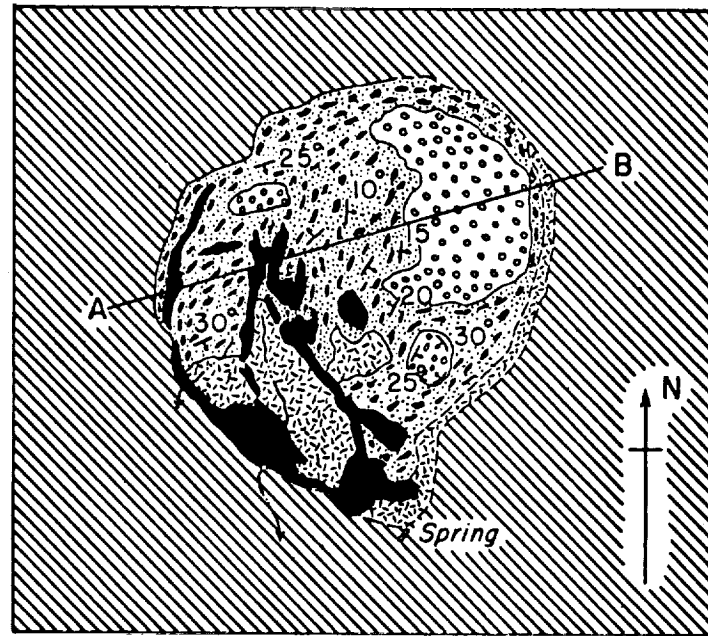


Figure 55. Map and section of a Hopi diatreme near Castle Butte Trading Post, Arizona. From J. T. Hack, 1942.

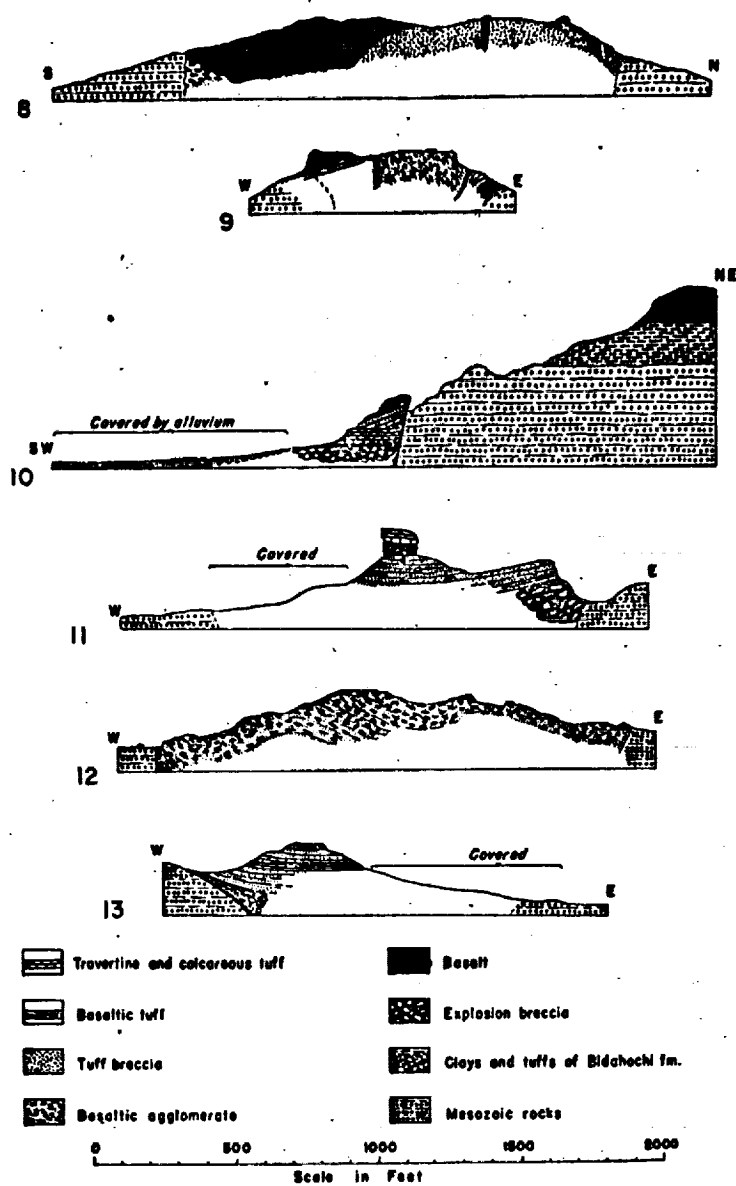


Figure 56 . Cross sections of six diatremes eroded below the Hopi Buttes surface, Arizona. From J. T. Hack, 1942.

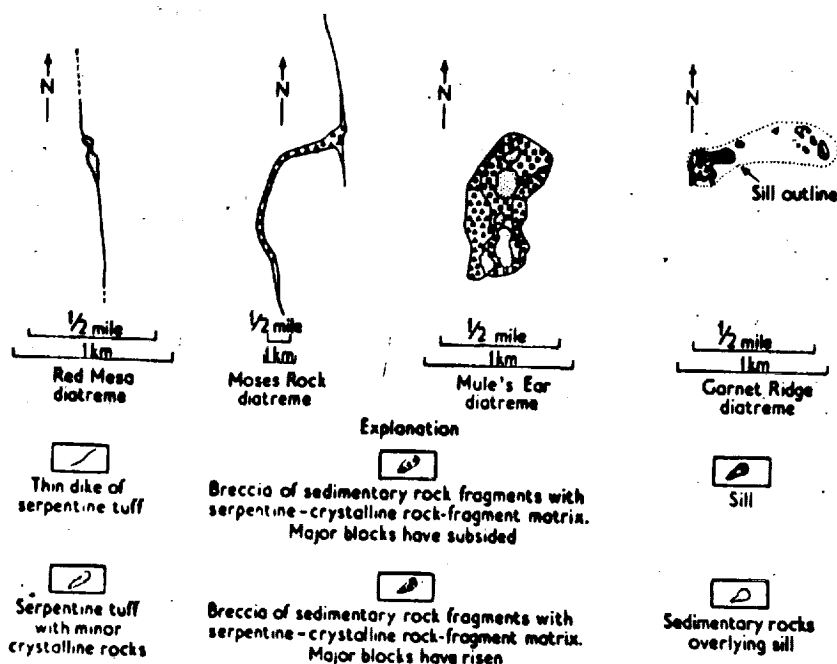


FIG. 3. Diagrammatic plan views of four serpentine-bearing diatremes in the northern part of the Navajo Indian Reservation, Arizona.

Figure 57. Diagrammatic plan views of four serpentine-bearing diatremes in the northern part of the Navajo Indian Reservation, Arizona and Utah. From Shoemaker, 1962.

4. Nature of fillings. Three kinds of fillings can be distinguished. a. Juvenile, magmatic material, in the form of dikes and as pyroclastic debris that varies from fine ash to coarse agglomerate and occasionally agglutinate. b. Lithic materials, from dust-size to giant blocks, derived from Mesozoic and Paleozoic wall-rocks, along with subordinate fragments of plutonic and metamorphic rocks torn from the Precambrian basement. c. Bedded fluviatile, lacustrine, and pyroclastic material laid down in maars and other circular depressions at the surface and subsequently downdropped within the diatremes. The ratios between these three kinds of diatreme-fillings vary greatly, not only from one diatreme to another, but in different parts of the same diatreme. And in virtually all diatremes, the filling materials are firmly cemented by calcite precipitated mainly from late hydrothermal solutions.

a. Consider first the magmatic materials. These are all of alkaline, basic and ultrabasic composition. Within and near the Hopi diatremes, the dikes, lavas, and pyroclastic ejecta consist of limburgite, monchiquite, and sanidine trachybasalt; within and near the Navajo diatremes, on the other hand, flows of trachybasalt are relatively rare, and the dikes and pyroclastic ejecta consist chiefly of potash-rich minette and in a few instances of phlogopite-bearing serpentine (kimberlite).

The monchiquites and limburgites tend to be rich in Ti, P, Zr, Ba, Ni, and the cerium-group rare earths; the minettes are rich in K, Ba, Sr, Be, Bo, the cerium-group rare earths, Pb, and H₂O. Radioactivity is anomalously high in both kinds of magma, but especially in the minettes.

Considering the much greater abundance of lavas in the Hopi Buttes and the greater abundance of pyroclastic debris in most of the Navajo diatremes, it seems probable that the strongly potassic minette magmas were more explosive than the sodic limburgite and monchiquite magmas.

Dikes. Most of the dikes between the diatremes of the Hopi Buttes are less than a meter wide, though a few reach 3 m. in width and one measures 12 m. across. Some are traceable at intervals for many kilometers, and none of the straight dikes departs more than 10° from the vertical. However, three Hopi diatremes are partly surrounded by arcuate dikes (cone sheets) that dip inward at low angles. Within the diatremes themselves the dikes are extremely irregular in trend and width and many of them are anastomosing; most of them were intruded after explosive activity had ended though some were emplaced late in the explosive phase. Dikes are no less common within and between the Navajo diatremes. Those within the pipes are irregular in width and trend; those that border the Boundary Butte diatreme are arcuate, whereas those associated with the Ship Rock diatreme are radial, one of them extending outward as a vertical wall 3 m. wide for a distance of 3 km. All but a few of the Navajo dikes are composed of minette; the exceptions consist of kimberlite-serpentine breccia.

Lavas. Flows of limburgite and monchiquite welled up quietly into many of the Hopi diatremes after explosive eruptions ended, and in some cases after partial subsidence of the fillings. These quiet effusions produced broad, low domical mounds above the diatremes or spread far beyond, where they now form the caps of extensive mesas. Other lavas were fed by dikes that were independent of diatremes. In the Chuska Mountains of the

Navajo country, several thick flows of trachybasalt accumulated in deep valleys during the closing stages of volcanism, but none of the Navajo diatremes is capped by lava as are many in the Hopi Buttes.

Magmatic ejecta. Most magmatic ejecta within and around the Hopi diatremes consist of angular and subangular chips of dark limburgite and monchiquite mingled with fragments of sedimentary rocks. True bombs and scoriaceous lapilli are exceptional. Ejecta blown out of the diatremes were quickly mixed with fluviatile and lacustrine deposits; those that accumulated within the upper parts of the diatremes show gentle inward dips, whereas those at deeper levels generally exhibit only faint bedding until all stratification finally disappears. But no matter at what level a diatreme is exposed, the magmatic and lithic ejecta are thoroughly admixed.

The great scarcity of rounded bombs and lapilli among the juvenile materials in the Navajo and Hopi diatremes suggests that the magmas were fairly viscous and the ejecta were quickly chilled. In some Hopi diatremes, however, the flaring upper parts contain coarse agglomerates with sub-rounded bombs and, more rarely, masses of agglutinate that must have been discharged in a fluid condition.

b. Lithic materials. Exotic fragments--i.e. fragments of wall-rocks and basement-rocks--mingled with magmatic debris vary greatly in amount from one diatreme to another and within some diatremes they tend to diminish in abundance at depth. In the Twin Cones diatremes, near Gallup, fragments of Cretaceous sandstone, for the most part finely pulverized, make up roughly 90 per cent of the filling, the remainder consisting of

minette dikes, lapilli and occasional blocks. In the serpentine-rubble diatremes of Garnet Ridge, exotic fragments make up about two-thirds of the fillings. The content of exotic materials is generally greater in the Navajo than in the Hopi diatremes, and is generally lower in small diatremes than it is in large ones.

Lithic fragments vary in size from minute particles to blocks several tens of meters across. Large blocks are usually angular and were derived by inward slumping and 'backfiring' of sedimentary wall-rocks. Fragments more than 3 m. across generally sank, sometimes to depths of more than 600 m. However, many large blocks were carried upward for long distances. In the Moses Rock breccia dike, for instance, slabs of Pennsylvanian limestone up to 30 m. in length were carried upward approximately 250 to 750 m. According to McGetchin, gas-pressures within this breccia dike were never adequate to lift rock-spheres measuring more than 30 m. in diameter. In most diatremes, uplifted fragments are most numerous in the central parts whereas downdropped fragments are most numerous near the margins.

In contrast to the large blocks derived from the sedimentary wall-rocks enclosing the upper parts of the diatremes, most of which are angular or are smooth, striated, and polished only on edges and corners, fragments from the Precambrian crystalline basement are invariably small and many are so well-rounded that they have been mistaken for pebbles and cobbles of fluvial and glacial origin. They range from sand-size to boulders slightly more than a meter in maximum dimension. Neither these nor the fragments of Paleozoic and Mesozoic sedimentary rocks in the diatremes show

more than rare signs of weak thermal metamorphism.

Size frequency distributions of the clastic sedimentary fragments in the Moses Rock breccia dike are, according to McGetchin, similar to those of materials comminuted in ball mills. However, the curves for limestones and crystalline basement fragments, perhaps because of their greater resistance to grinding, are not as clearly indicative of such comminution.

The depths from which lithic fragments were uplifted may, in Shoemaker's opinion, denote the depths at which boiling took place in the magmas that fed the diatremes, and may also be correlated with the type of associated magmatic materials. Thus, the kimberlite-bearing diatremes of the Navajo country contain a wide variety of Precambrian rocks, mostly mafic, whereas in the nearby minette-bearing diatremes the principal kinds of crystalline basement fragments are granitic, and in the monchiquite-bearing Hopi diatremes even granitic fragments are rare, almost all of the lithic debris consisting of Paleozoic and Mesozoic sedimentary rocks. The greatest depths from which lithic fragments were uplifted was probably more than 1,500 m. below the Pliocene eruption-surface.

c. Bedded fluviatile, lacustrine, and pyroclastic materials.

The upper parts of many diatremes are occupied by well-bedded, inward-dipping deposits that pass downward gradually through less distinctively bedded and more steeply dipping deposits into unstratified deposits and massive igneous rocks. Some of these stratified deposits are products of 'backfalls' of ejecta into the eruptive vents. Examples may be seen in

the upper parts of several Navajo diatremes, such as Barber Peak, Ship Rock, and Agathla. Clearly, however, most of the well-bedded deposits within the Hopi diatremes were laid down by streams, by inwash of debris into maars, and by evaporation of evanescent lakes. Fluvial beds display characteristic cross-bedding and channeling; lacustrine beds consist of thinly laminated silts and clays; and evaporites include travertine, gypsiferous and cherty beds. Their aggregate thickness in some diatremes exceeds 100 m. and in a few it exceeds 600 m. This is not because the initial explosion-vents were deep; on the contrary, those diatremes that broke through to the surface ended in shallow basins surrounded by low rims of pyroclastic ejecta. Slow accumulation of sediments during concomitant subsidence accounts for the great thickness of the deposits. The scarcity of interbeds of airfall pyroclastic debris and of impact pits made by falling fragments implies that explosive activity had almost stopped before sedimentation and subsidence began within the diatremes.

Subsidence of diatreme-fillings. The main explosive phase of some diatremes may have been accompanied by inward slumping of the rims of maars and by near-surface collapses of the walls along ring-fractures. There can be no doubt, however, that subsidence also took place at depth after explosive eruptions had ceased, thus permitting long-continued sedimentation at the tops of the diatremes.

Among the suggestions that have been made to account for the subsidences, there are several that may be dismissed as improbable and inadequate, e.g. solution of limestone, compaction of gas-charged ash, and contraction of magma during solidification. Shoemaker and his colleagues considered

the most likely cause to have been foundering of fragmental materials into underlying columns of still liquid magma, and they suggested that magmatic stoping and assimilation of sedimentary and pyroclastic debris may have been facilitated by convection currents, in the manner postulated by McBirney. While admitting the likelihood that foundering and stoping played a role in the subsidence of some diatreme-fillings, it seems more probable that subterranean withdrawal of magma was the dominant agent. The diatremes were fed through a network of dikes, and some of them, though lying on a common fissure, reached different stages of development at the same time. Magma appears to have risen in one diatreme on a fissure-system and then migrated underground to rise in another. Indeed, in the opinion of this reviewer (H.W.), many diatremes in the Hopi country failed to break through to the surface to produce maars; instead, tongues of magma rose into flat-lying lacustrine and fluviatile beds and then gradually withdrew, causing circular basins to form within which additional waterlaid sediments slowly accumulated. For this reason, most of the well-bedded deposits within the Hopi diatremes resemble those that make up the Pliocene Bida-hochi formation in the surrounding regions (figures 55 and 56).

Mode of development of the diatremes. Initial stages in the formation of most Navajo-Hopi diatremes were marked by explosive drilling of vents by rising gases, and by the development locally of craters and maars at the surface, each enclosed by a low rim of ejecta. Kerr, Shoemaker, and others have supposed that all of the gases were exsolved from underlying bodies of ultramafic magma. More recently, Kennedy and Nordlie (1968) have suggested that some kimberlite pipes in other regions may have been

(Diatremes of the Navajo-Hopi Country)

drilled in part by gaseous CO_2 liberated by fracturing of deep-seated mantle-rocks containing crystals of olivine with liquid inclusions of CO_2 . However, McBirney has demonstrated that the breccia-filled diatreme near Cameron, Arizona, cannot have been produced primarily by magmatic gases, at least at the present level of exposure, but must have resulted from steam-blast (phreatic) eruptions when rising magma came into contact with abundant groundwater in the Navajo Sandstones.

There can be little doubt that the ultramafic magmas associated with the Navajo and Hopi diatremes were rich in volatiles, chiefly H_2O and CO_2 . There can be even less doubt that steam-blast (phreatic) eruptions also played an important part in the development of all the Hopi diatremes and many of the Navajo diatremes, at least in their upper parts. More than half of the Hopi diatremes rose into the floor of the Pliocene Hopi Lake, and the remainder rose into adjacent, watersoaked floodplains; similarly, the upper parts of many of the Navajo diatremes must have penetrated abundant groundwater. It goes without saying, therefore, that when rising magma and hot magmatic gases closely approached the Pliocene surface, there must have been recurrent steam-blasts. Admittedly, no instances have been described of an upward transition from purely lithic debris blown out by steam blasts to ejecta increasingly charged with magmatic debris, but this is probably because erosion has removed the evidence. Near-surface steam blasts, by hurling out much lithic debris and forming funnel-shaped craters would have reduced pressure on underlying bodies of magma and so have promoted deeper and more rapid exsolution of magmatic gases. Though the initial, deep-seated fractures were probably wedged apart by rising magma and magmatic gases, further development of many

diatremes must have been facilitated by steam blasts close to the surface.

Rising gases, more or less charged with magmatic ejecta, not only wedged apart the overlying rocks but fragmented and abraded them to produce a fluidized gas-solid system. Subsequently, as gas velocities increased within the diatremes and gas pressures diminished, parts of the walls 'backfired' into the pipes, and the resultant blocks were slowly comminuted and mixed with the magmatic materials in the fluidized system. At depth, the 'backfiring' of wall-rocks into the diatremes was sudden and violent; close to the surface, decompression led to more gradual slumping of the diatreme-walls.

Small fragments torn from the Precambrian crystalline basement were abraded and polished in the fluidized system and thoroughly admixed with the debris derived from the overlying Paleozoic and Mesozoic sedimentary rocks. Some blocks of wall-rocks sank in the fluidized system until they attained equilibrium; others rose, either because they were smaller or because they became entrained in faster-moving currents of gas; still other fragments, after sinking for a time, were comminuted so that the separate fragments were carried upward.

Relatively little debris was blown out of the diatremes, for the only violent explosions were near-surface steam blasts. In most diatremes, the explosive phase was followed by quiet upwelling of magma, some of which solidified at depth to form dikes, while some solidified as crater-fillings and some poured over the crater-rims to spread as extensive lava flows.

Slow subsidence of the fillings of diatremes may already have

begun during the explosive phase, owing to stoping of debris by underlying magma, but more often it took place when magma was gradually withdrawn at depth to feed adjacent diatremes located on a common fissure-system. And while the surficial, circular basins sank, the fluviatile and lacustrine sediments and evaporites accumulating on their floors sank with them into the diatremes.

Diatremes in the 'Missouri River Breaks', Montana
(Hearn, 1968)

Diatremes with kimberlitic affinities are scattered in a broad belt that trends east-northeast for 160 km. through the 'Missouri Breaks' of north-central Montana. Exposures are exceptionally good, and the stratigraphic sequence of the surrounding rocks, which range in age from Pre-Cambrian to early Eocene, is well-known. The fillings of the diatremes consist of lithic debris derived from the walls and juvenile material, mostly monticellite peridotite and alnoite.

The diatremes, as now exposed, are surrounded at the surface by Cretaceous sediments, but when they were formed they pierced an erosion-surface, cut in post-middle Eocene and pre-Miocene beds, at least 1,280 m. above the deepest of the present exposures.

Most of the diatremes are approximately circular to elliptical in plan, with diameters ranging from 46 to 518 m. Their walls are nearly vertical, and some of the larger diatremes are surrounded by a zone of down-dragged wall-rocks that varies from 30 to 60 m. in width. The typical internal structure is marked by a discontinuous collar of downfaulted, sheared, arcuate slices of sedimentary wall-rocks that stand vertically. Because of frictional drag against the marginal ring-faults, the inner slices of sedimentary rock subsided more than the outer ones, which means that towards the center younger rocks are found. The maximum subsidence was 1,280 m.

The collar of sliced sediments is partly separated from the marginal ring-fault in some diatremes by a narrow, discontinuous ring-dike of either intrusive tuff or solid monticellite peridotite. Within the collar lie well-bedded ultramafic tuffs that generally dip inward to a

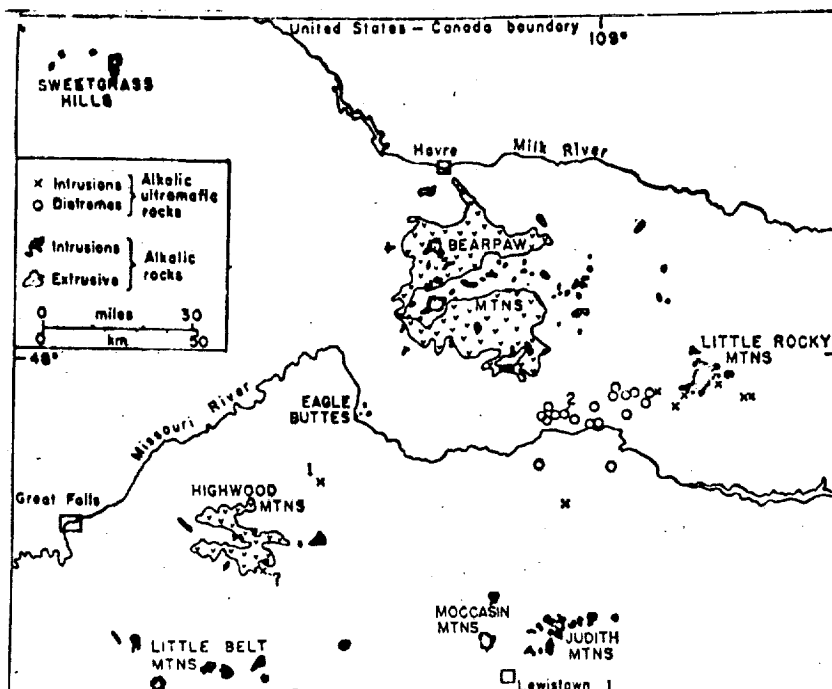


Fig. 1. North-central Montana: locations of diatremes and intrusions of alkalic ultramafic rocks in relation to alkalic igneous centers of the Bearpaw, Highwood, Little Rocky, Judith, Moccasin, and Little Belt mountains, Sweetgrass Hills, and Eagle Buttes. 1, Haystack Butte; 2, Black Butte. [Geology modified from Geologic Map of Montana (22)]

Figure 58. Map of North-central Monatana, showing location of diatremes. From Hearn, 1968.

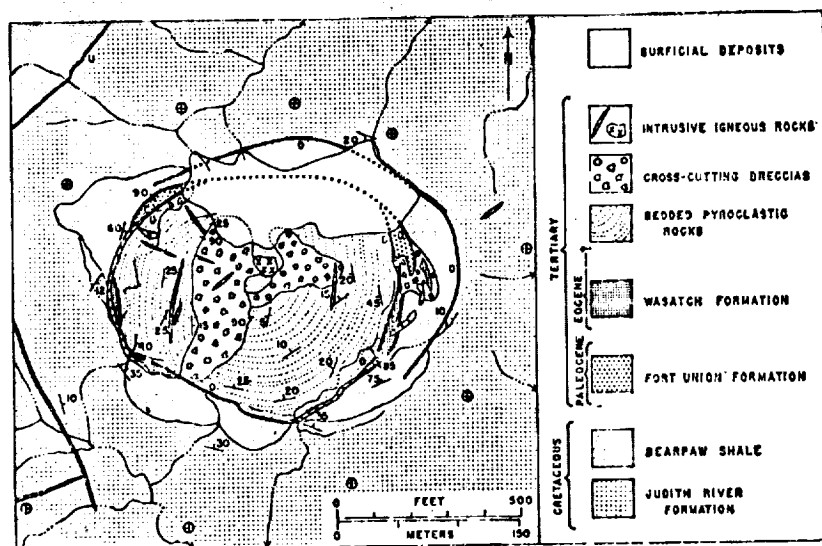


Fig. 1. Generalized geologic map of Black Butte diatreme in NE1/4 sec. 20; T. 24N; R. 20E, Blaine County, Montana; geologic symbols are standard. Fault in northwest corner is northwest boundary of uplifted hostlike block within a linear fault-fold structure penetrated by the diatreme.

Figure 59. Generalized geological map of Black Butte diatreme. From Hearn, 1968.

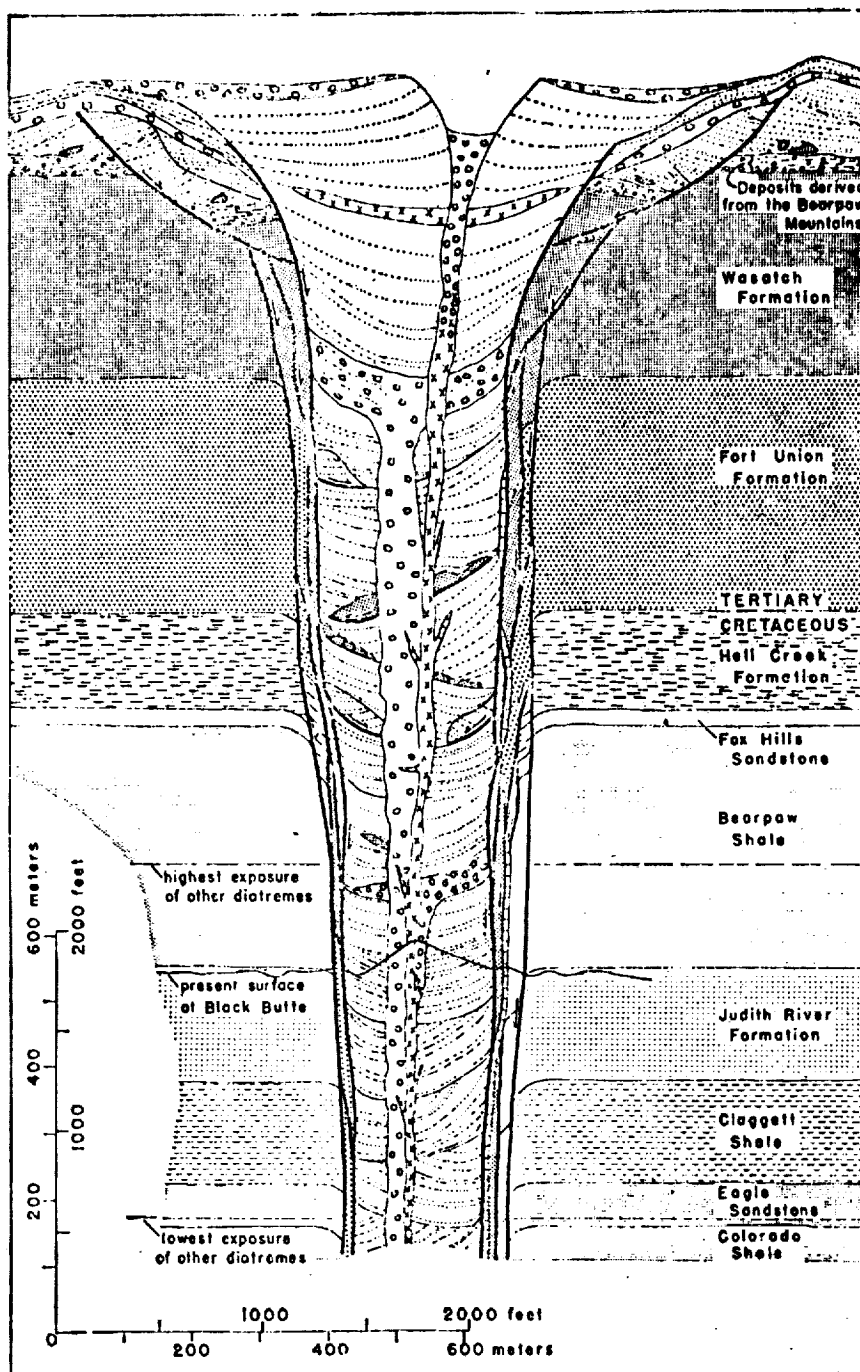


Fig. Diagrammatic cross section, based on the Black Butte diatreme, showing inferred geologic structure up to the surface of eruption. Structure inferred below the surface of eruption is generalized from features seen in other diatremes in north-central Montana. Note the present surface at Black Butte, and the upper and lower limits of exposure of wall rocks of other diatremes. Igneous units patterned as in Fig. 2.

Figure 6Q Diagrammatic cross section of a diatreme, based on the Black Butte diatreme. From Hearn, 1968.

(Diatremes in the 'Missouri River Breaks', Montana)

central or eccentric core of unbedded intrusive breccia, accompanied by dikes and irregular intrusive bodies of massive ultramafic rock.

The bedded tuffs tend to form saucer-shaped structures, steep dips near the walls of the pipes changing to shallow dips near the centers. Angular unconformities within the tuffs are not uncommon, perhaps denoting intermittent subsidences during the eruptive activity. Graded bedding, though faint, denotes some gravity sorting of the ejecta, and the presence of occasional impact pits made by falling blocks may imply that some ejecta were laid down at the surface.

The tuffs consist of ultramafic fragments rich in altered olivines, admixed with lithic fragments derived chiefly from Cretaceous, Paleocene, and Eocene beds. Some lithic fragments were derived from Jurassic and Paleozoic beds, and in three pipes there are fragments derived from still deeper levels. These include fragments of schist, biotite-pyroxene-carbonate rocks, garnet-clinopyroxene-plagioclase-rutile granulites, garnet-pyroxene peridotites, and many individual crystals of garnet. They must have been carried up from the lower part of the crust and from the underlying upper mantle.

Abundant ovoid juvenile lapilli, from pea-size to more than inch in maximum dimension, are to be seen in some diatremes, concentrated mainly in irregular, upward-tapering, cupola-like bodies, several feet high, above intrusions of massive ultramafic rock. Typically, each lapillus has an olivine phenocryst or small lithic fragment in the core, and shows a tangential alinement of lath-shaped crystals in the envelope. A few lapilli have equatorial flanges. All were formed by explosive disruption of gas-rich magma; their shapes were determined partly by surface tension

(Diatremes in the 'Missouri River Breaks', Montana)

and partly by rotation in open spaces above the effervescing magma. The skins of the lapilli were chilled sufficiently in flight to prevent them from sticking together to produce agglutinate after the lapilli came to rest.

The diatremes were drilled to the surface during rise of monticellite peridotite and alnoite magma from the mantle by rapid exsolution of a gas phase rich in carbon dioxide. The original diameter of each pipe was considerably increased by intermittent subsidence between ring-faults. Slices of sedimentary country rocks that were lying flat at and near the surface when the diatremes were initially formed now stand vertically near the margins of the pipes, enclosing steeply dipping, well-bedded pyroclastic deposits, most of which were almost certainly laid down sub-aerially. Both the sedimentary and pyroclastic rocks subsided intermittently during, and probably also after volcanism ended.

Pipes in New South Wales, Australia
(Wilshire, 1961)

A group of poorly exposed volcanic conduits that cut Triassic sediments in New South Wales were probably formed by Tertiary alkali-basalt eruptions. At the present surface, the pipes are irregular in shape and have diameters of up to 850 m. At the time of their formation, the pipes at Minchenbury Farm, Erskine Park, and Richardson's Farm are assumed by Wilshire to have had a cover of not more than a few hundred feet; the Hornsby pipe had a cover of 350 m. or less.

The breccias consist of fragments of country rocks--shale, sandstone, siltstone, coal, basalt, granite, gabbro, quartzite--with altered or fresh alkali basalt and ultramafic nodules. The source of the coal lies at a depth of about 1000 m.; the sources of the granite and quartzite lie at more than 3300 m., whereas the ultrabasic nodules are believed to come from the upper mantle and to have been disaggregated at depth from the basalt which carried them. Pisolites in one pipe, up to 7.5 cm. in diameter, contain detrital cores and concentric layers of finer-grained material. Fragments of pebble-size are usually angular whereas those of boulder-size may be well-rounded.

Layering of the breccias, which is very conspicuous, is expressed by size-sorting. Individual layers are 1 to 50 cm. thick. Elongated particles are oriented within the plane of layering. Cross-layering, locally with high-angle truncation, is quite common but graded layering has not been observed. Pebbles are scattered through the breccias, and where the latter are finely laminated the laminae bend around the pebbles.

Coarse fragments are concentrated on one side of the pebbles and may be traced for about a meter.

In the eastern part of the elongated Hornsby pipe, layering and numerous small-scale faults and slickensides are arranged in a large scale funnel structure, whereas in other pipes these elements do not show a regular arrangement.

Layering is also found around large blocks up to 50 m. in diameter; it may be folded and faulted. At the southwestern margin of Erskine Park diatreme, breccia dips 22° to 55° under sandstone and shale of the country-rock which are strongly faulted and folded for about 30 m.

Wilshire believes that near the surface the breccias were forcefully injected into the country rocks, which were lifted, wedged aside, folded and faulted, without being brecciated or incorporated in the intrusion. The layering is interpreted as the result of flow in a very viscous aggregate during forceful emplacement of the intrusive breccia, and variation in grain-size in different layers is thought to have been due to differences in their velocity. In Wilshire's opinion, layering due to sorting in airfalls was out of the question. Whether or not any of the pipes reached the surface is uncertain. At greater depth, fluidization is believed to have played an important role, e.g. in the rounding of boulder-sized blocks, mixing of fragments, and enlargement of the pipes. The presence of granite and quartzite fragments indicates that gas-transport was already active at a depth of at least 3000 m. Lack of coking of coal fragments points to temperatures below 250° in the upper 1000 m. of the pipe.

The gases transporting all fragments upward in the pipe are assumed to be partly of juvenile origin and partly from groundwater, coal and other organic sources.

Wilshire excludes the possibility that the breccias were deposited subaerially and then subsided into the pipes. The angles of cross-bedding are too high to be angles of repose. There is no graded bedding, the pipes are dike-like, and large blocks are surrounded by layered breccias; all these features, according to Wilshire, exclude a subaerial origin. It is possible, however, that subaerial slumping could produce high angles in cross-bedding and that graded bedding may not be developed in the immediate neighborhood of an orifice. Nor is the dike-like shape necessarily an obstacle, especially since the minimum dimension of some of the dike-like pipes is about 50 m. The occurrence of large blocks of country rock up to 50 m. across within layered breccias could be explained by caving of the walls during and after subsidence had taken place, especially since Wilshire describes these blocks only from those pipes which had a cover of no more than 100 m. Moreover, the occurrence of pisolites (accretionary lapilli) in one pipe suggests subaerial deposition (Moore 1962). Pisolites normally require open space to form and disintegrate or crush when subjected to differential movements and stresses.

Wilshire argues that well-developed layering is inconsistent with gas or liquid fluidization at the levels now exposed; however, he does not explain the mechanism of flow responsible for the broad layers composed almost entirely of solid fragmental material.

(Pipes in New South Wales, Australia)

Although it is difficult to dispute Wilshire's explanation without having examined the pipes ourselves, we feel that the case for a subaerial origin of the layering cannot be entirely dismissed. In many funnel-shaped structures, such as those of Scotland, Montana, Czechoslovakia, and Germany, there is strong evidence that the layering formed subaerially and reached its present level as the result of subsidence.

Diamond Pipes of South Africa

(Dawson, 1962; Wagner, 1914; Williams, 1932)

There are no finer examples of diatremes than the diamond-bearing kimberlite pipes of South Africa. Thanks to extensive mining to depths of a thousand or more meters the shapes, internal structure, and compositional variations of the pipes are fairly well known.

The South African pipes are part of a more extensive group of Late Cretaceous kimberlite diatremes that form a broad belt from Cape Province northward to the Congo and Tanzania. The pipes tend to be grouped in clusters of ten or twelve of which only a few may contain enough diamonds to be commercially exploited. At their present level of exposure, the pipes are several thousand feet below the surface at which they erupted. This can be shown from the numerous inclusions that can be traced to higher stratigraphic units long since eroded away. Diamonds from the eroded parts of the pipes are recovered from the sand and gravel of old water courses and from beaches and dunes along the coast near the mouth of the Orange River. Within the depths of mining the pipes penetrate metamorphic and plutonic rocks, Precambrian quartzites and lavas, and upper Paleozoic and lower Mesozoic sediments, lavas, and dolerite dikes and sills of the Karoo System.

The largest of the pipes, the Premier near Pretoria, has an elliptical surface outcrop measuring about 400 by 800 meters. Most of the pipes are much smaller, however, many being only a few tens of meters across. The pipes tend to become narrower and more elongated with depth. Some pass into dike-like bodies that follow a regional west-northwest trend. The contacts are sharp, and the surrounding rocks show no thermal metamorphism.

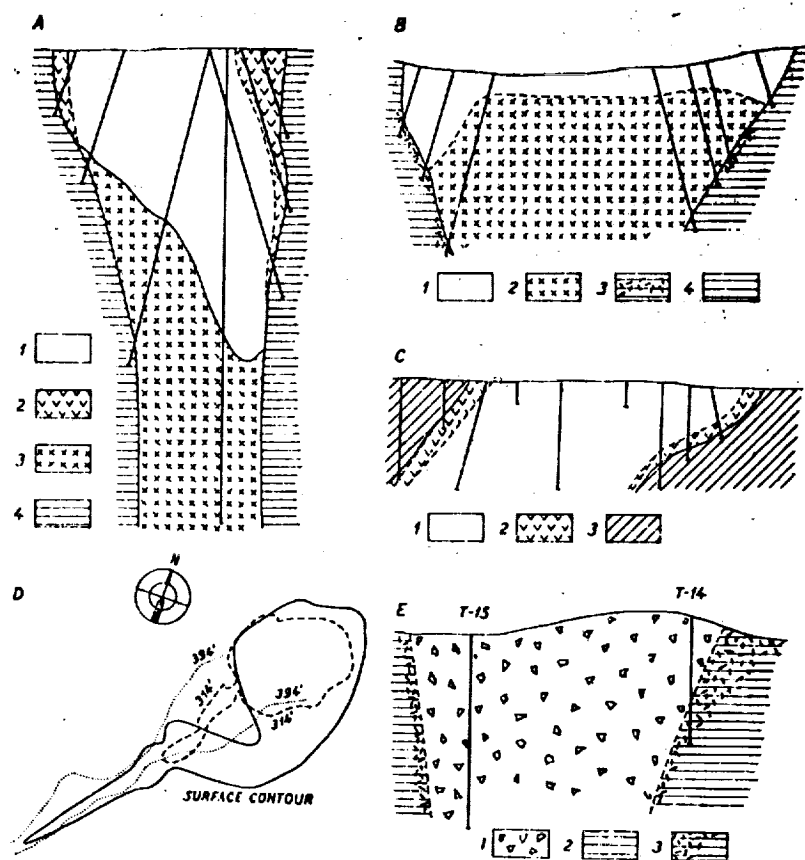
Vertical grooves have been observed on the walls, but there is little deformation that would indicate the wall rocks were forced apart by the emplacement of the pipe. Thin screens of wall rocks may be detached and suspended in the kimberlite a short distance away from the walls.

The internal structure is usually simple. Layering is faint or totally absent. The distribution of inclusions, including diamonds, is normally random, although in some pipes inclusions closer to the margins are predominantly from higher levels while inclusions in the central part of the pipe tend to be from deeper sources. Near the surface, the kimberlite is deeply weathered and oxidized to yellowish brown clay, the 'yellow ground' of miners. At greater depths, this gives way to 'blue ground' which is also altered but less oxidized. Only at the deepest levels of a few mines is the kimberlite unweathered.

The kimberlite is choked with rock and mineral fragments of all sizes and compositions. Most of the material is thoroughly altered and replaced with carbonates and serpentine. Rounded and polished inclusions of granulite, garnet peridotite, eclogite and other exotic rocks have been carried up into the pipe from unknown depths. Like the diamonds, the mineral assemblages of these inclusions indicate that they were formed at very high pressures, on the order of 120 kilometers.

The kimberlite itself is an ultramafic rock that is poor in silica and alumina and rich in magnesia. It normally contains at least 10 percent by weight of water and CO_2 . Large crystals of olivine, enstatite, chrome diopside, ilmenite, pyrope garnet and mica are embedded in a ground-mass of serpentine and calcite.

Early workers believed that the pipes had bored their way to the surface by great explosive eruptions. The absence of disturbance in the wall rocks, together with the enormous energy requirements of such an eruption clearly rule this out. It appears more likely that the pipes rose toward the surface by a less violent process. Abundant evidence of fluidization indicates that the kimberlite was emplaced as a gas-solid or liquid-solid system, probably at temperatures well below the melting temperatures of the rocks. Unfortunately, the high level features of the pipes have been removed by erosion and it is difficult to determine how the initial vent was formed.



3. Changes of the form of diatreme with depth

A — "Mir" diatreme (after A. P. BOHRJEVIĆ et al. 1959, Fig. 9): 1 — green altered kimberlite; 2 — yellow, slightly altered kimberlite; 3 — slightly altered dark-green kimberlite; 4 — carbonate rocks. B — "Mir" diatreme (after E. V. FRANCESCON 1962, p. 37): 1 — altered kimberlite; 2 — dark-green, slightly altered kimberlite; 3 — contact breccia; 4 — limestone. C — diatreme "Udačnaja" (after A. P. BOHRJEVIĆ et al. 1959, Fig. 21): 1 — contact-metamorphosed kimberlite breccia; 2 — carbonatized contact-metamorphosed kimberlite breccia; 3 — carbonate rocks. D — Kimberlite diatreme "Roberts-Victor Mine" (after A. F. Williams, 1932, I, p. 131) — narrowing of the diatreme at working levels and its transition into a dyke. E — "Šibenice" diatreme near Semeč in the Česká středohoří (L. Kopecký 1966): 1 — vent breccia; 2 — marlstone; 3 — contact breccia.

Fig. Changes of the form of diatremes with depth. (after Kopecký, 1966).

Avon Diatremes, Missouri
(Singewald, 1930; Rust, 1937)

The Farmington anticline, near the Ozark uplift, in the vicinity of Avon, Missouri, is pierced by 78 diatremes. Accompanying these are more than 12 dikes of altered lamprophyre, most of which follow conspicuous fault-zones. Here, as in the Schwabian Alb of southern Germany, the pipes appear to be younger than the dikes. Recent radiometric measurements indicate that the diatremes are of Devonian age (Zartmann et al., 1967).

The country rocks are Lower Cambrian sandstones, dolomites, limestones, and shales underlain at a depth of about 100 m. by granite. Fragments of Devonian rocks within the diatremes indicate that a large volume of material has been eroded above the present surface.

The pipes are approximately cylindrical and measure between a few meters and 100 m. across. Their vertical walls are intruded by small apophyses that run parallel and transverse to the sedimentary bedding. Except in pipes that contain a central core of ultrabasic intrusive rock, the fillings consist of pyroclastic material of conglomeratic appearance, composed of a mixture of juvenile and xenolithic ejecta. Some pipes are almost wholly filled with one or the other type of material, but most contain an abundance of both.

Lithic debris includes fragments of granite brought up from depth, Cambrian sedimentary rocks torn from the adjacent walls, and Devonian limestones that must have subsided more than 1,000 m. The largest lithic blocks exceed 3 m. across.

The juvenile material is composed of alnoite, characterized particularly by the presence of abundant spheroidal and ovoid lapilli

(Avon Diatremes, Missouri)

(pellets) measuring 0.1 to 3 cm. in diameter. Each lapillus has a nucleus consisting either of a phenocryst from the ultramafic magma or an angular lithic chip, but the shapes of the nuclei appear to have had no influence on the shapes of the lapilli. The material surrounding the nuclei is either glassy or microcrystalline, and contains phenocrysts of pyroxene, grains of titaniferous magnetite, and small laths of feldspar arranged tangentially with respect to the surfaces of the lapilli.

Formation of the pipes is believed to have started with intrusion of a laccolith that caused adjustments of the roof and so provided channels for the intrusion of dikes. Crystallization of the magma is then supposed to have caused gas-pressure to increase until it exceeded the strength of the roof. When this occurred, the sudden release of pressure permitted rapid exsolution of gases rich in carbon dioxide with the result that the magma burst into a spray that coalesced around solid particles to produce droplets. Surface tension and rotation of the droplets combined to yield the rounded lapilli with their concentrically enclosed laths of feldspar.

Enlargement of the pipes seems to have been aided by brecciation of the walls and subsequent 'backfiring' of fragmented wall-rocks when gas-pressures within the pipe diminished. During the final, hydrothermal stages of activity, the pipe-fillings were cemented by deposition of carbonates, sulphides, and oxides. The gas-phase responsible for the eruptions is assumed to have been partly of magmatic origin and partly derived by reaction with Cambrian carbonate-rocks.

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